THE ROLE OF *PHRAGMITES AUSTRALIS* IN CARBON, WATER AND ENERGY FLUXES FROM A FEN IN SOUTHWEST GERMANY

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SUMMARY

About one-third of the global soil carbon is stored in peatlands. Although carbon storage has a positive contribution to climate change mitigation, peatlands also emit a large amount of greenhouse gases. The global carbon emission from peat soils adds up to 0.1 Gt-C per year. Under anaerobic conditions, organic material is decomposed to methane (CH_4). Over a 100-year cycle, methane is a 28 times stronger greenhouse gas than carbon dioxide and is an important factor for climate change. Wetlands (including peatlands) are responsible for 22% of all the CH_4 emissions world-wide. Moreover, many peatlands are disturbed due to excavation and drainage for conversion to agriculture land, resulting in a 9-15% of the global greenhouse gas emission in carbon dioxide equivalents (CO_2-eq). Therefore, there is a great interest to get a better understanding of the carbon flows in peatlands. *Phragmites* peatlands are particularly interesting due to the global abundance of this wetland plant (*Phragmites australis*, common reed) and the highly efficient internal gas transport mechanism. This is a humidity-induced convective flow (HIC) to transport oxygen (O_2) to the roots and rhizomes, with the effect that simultaneously soil gases (CH_4 and CO_2) can be transported to the atmosphere via the plant. Thereby, *Phragmites* is expected to have a high evapotranspiration (ET) rate due to the large leaf area, open water habitat and high aerodynamic roughness. This ET could highly influence the hydrology of the system. Because he accumulation of organic material occurs because of limiting oxygen levels, hydrological processes are fundamental in the development of peatlands.

The research aims were: 1) to clarify the effect of plant-mediated gas transport on CH_4 emission, 2) to find out whether *Phragmites* peatlands are a net source or sink of greenhouse gases, and 3) to evaluate ET in perspective of surface energy partitioning and compare results with FAO's Penman-Monteith equation. CO_2, CH_4 and latent and sensible energy fluxes were measured with the eddy covariance (EC) technique within a *Phragmites*-dominated fen in southwest Germany in 2013, 2014 and 2016. In 2016, a field experiment was set up to quantify the contribution of plant-mediated CH_4 transport to the overall CH_4 flux and how it influences ebullition.

One year of EC flux data (March 2013–February 2014) shows very clear diurnal and seasonal patterns for both CO_2 and CH_4. The diurnal pattern of CH_4 fluxes was only visible when living green reed was present. In August the diurnal cycle of CH_4 was the most distinct, with 11 times higher midday fluxes than night fluxes. This diurnal cycle had the highest correlation with global radiation, which suggests a high influence of HIC on CH_4 emission. But if the cause were HIC, relative humidity should correlate stronger with CH_4 flux. Therefore, we conclude that in addition to HIC at least one other mechanism must have been involved in the creation of the convective

flow within the *Phragmites* plants. We quantified the influence of pressurized flow within *Phragmites* on total CH_4 emission in a field experiment (see chapter 3) and found between 23% and 45% lower total CH_4 flux when pressurized flow was excluded (by cutting or cutting and sealing the reed). The gas transport pathways from the soil to the atmosphere changed as well. Relative contribution of ebullition to the total flux increased from 2% in intact *Phragmites* to 24-37% in cut vegetation. This increase in ebullition in cut vegetation, obviously, did not compensate the excluded pathway via the pressurized air flow at our site. It also means that the effect of CH_4 bypassing the oxic water layer by plant transport on CH_4 emission is much larger than the effect of O_2 transport through the plants on CH_4 oxidation and production in the rhizosphere.

Overall, the fen was a sink for carbon and greenhouse gases in the measured year, with a total carbon uptake of 221 g C m^{-2} yr^{-1} (26% of the total assimilated carbon). The net uptake of greenhouse gases was 52 g CO_2 eq.m^{-2} yr^{-1}, which is obtained from an uptake of CO_2 of 894 g CO_2 m^{-2} yr^{-1} and a release of CH_4 of 842 g CO_2 eq.m^{-2} yr^{-1}. Compared to the long term uptake of carbon by northern peatlands (20–50 g C m^{-2} yr^{-1}) 212 g C yr^{-1} is therefore very high. One year of measurements is not enough to draw hard conclusions about the climate change impact of this peatland.

The measured ET at our site was lower than other *Phragmites* wetlands in temperate regions. ET was half the amount of precipitation (see chapter 4). Therefore, the risk of the wetland to dry out is not realistic. ET was especially low when there was little plant activity (May and October). Then, the dominant turbulent energy flux was sensible heat not latent heat. This can be explained by the high density of dead reed in these months. the reed heats up causing a high sensible heat flux. Evaporation was low due to the shading of the water layer below the canopy and low wind velocities near the surface. FAO's Penman-Monteith equation was a good estimator of measured ET with crop factors from the regression model of Zhou and Zhou (2009) (see chapter 4). Especially the day-to-day variation was modeled very well. Their model had air temperature, relative humidity and net radiation as input variables. This is likely related to stomatal resistance, which depends on the same variables. Therefore, the model of Zhou and Zhou (2009) is an interesting tool for calculating daily crop factors and it is probably robust enough to be used also in different regions.

ZUSAMMENFASSUNG

Die globale Aufnahme von Kohlenstoff in Torfböden beträgt bis zu 0,1 Gt-C pro Jahr. Etwa ein Drittel dieses im Boden gebunden Kohlenstoffs, befindet sich in Mooren. Obwohl dieser Speicher einen positiven Beitrag zur Abschwächung des Klimawandels leistet, stoßen Moore gleichzeitig auch große Mengen an Treibhausgase aus. Aufgrund anaerober Bedingungen im Boden, wird organisches Material zu Methan (CH_4) abgebaut. Über einen Zeitraum von hundert Jahren ist CH_4 ein um das 28-fache stärkere Treibhausgas als Kohlenstoffdioxid und damit ein wichtiger Faktor der Klimaveränderung. Feuchtgebiete (inkl. Mooren) sind für 22% des weltweiten Methan-Ausstoßes verantwortlich, wobei 9-15% der globalen Treibhausgasemission, gemessen in Kohlenstoffdioxid-Äquivalente (CO_2-Äq.), aus abgegrabenen oder für die Landwirtschaft trockengelegten Mooren stammen. Daher besteht Interesse am Verstehen des Kohlenstoffkreislaufes in Mooren. Schilf-bewachsene Moore (*Phragmites*-Moore) sind dabei von besonderem Interesse, da diese Pflanze (*Phragmites australis*, Schilfrohr) weltweit in vielen Gebieten vorkommt und über einen hoch-effizienten internen Mechanismus zum Gastransport verfügen. Der Transport von Sauerstoff (O_2) zu den Wurzeln und Rhizomen beruht auf Luftfeuchtigkeit-induzierten konvektiven Fluss (HIC), wobei gleichzeitig auch Bodengase (CH_4 und CO_2) durch die Pflanze in die Atmosphäre transportiert werden können. Aufgrund der großen Blattfläche, des Lebensraums im offenen Wasser und eine hohen aerodynamischen Rauheit, wird daher erwartet, dass *Phragmites* eine hohe Evapotranspirationrate (ET) aufweist. Diese ET-rate könnte maßgeblich die Hydrologie des Systems beeinflussen. Die Zunahme von organischem Material, aufgrund limitierender Sauerstoffgehalte und hydrologischer Prozesse ist grundlegend für die Entwicklung von Mooren.

Die Forschungsziele waren 1) zu verdeutlichen, welche Rolle der Gastransport durch die Pflanzen auf die CH_4-Flüsse hat, 2) ob *Phragmites*-Moore ein Netto-Quelle oder eine Netto-Senke für Treibhausgase sind und 3) die ET im Hinblick auf Sonnenenergie-Aufteilung zu messen, um diese mit der aus der FAOs Penman-Monteith Gleichung berechneten ET zu vergleichen. CO_2, CH_4 , sensible und latente Energieflüsse wurden 2013, 2014 und 2016 mit der Eddy-Kovarianz (EK) Methode in einem von *Phragmites* dominierten Moor im Südwesten Deutschlands gemessen. 2016 wurde ein Experiment durchgeführt, um den Beitrag des CH_4-Transports durch die Pflanzen zum gesamten CH_4-Fluss zu quantifizieren und dessen Einfluss auf Ebullition (Bildung von Gasblasen) zu ermitteln.

Die EC-Daten eines Jahres (März 2015 bis Februar 2014) zeigen sehr deutliche tageszyklische und saisonale Muster sowohl für CO_2 als auch für CH_4. Die tageszyklischen CH_4-Flüsse waren nur zu erkennen, wenn grünes, lebendes Schilf anwesend war. Dieser Tageszyklus korreliert am meisten mit der Globalstrahlung, was einen hohen Einfluss von HIC auf die CH_4-Flüsse vermuten lässt. Sollte HIC die Hauptursache sein, müsste eine stärkere Korrelation zwischen relativer Luftfeuchtigkeit und den gemessenen CH_4-Flüssen festzustellen sein. Da dies nicht der Fall ist, schließen wir, dass es noch mindestens einen weiteren Mechanismus gibt, der in der Erzeugung der Konvektionsströmung innerhalb der *Phragmites*-Pflanzen involviert ist. Wir haben in einem Feldexperiment quantifiziert, welchen Einfluss die Konvektionsströmung innerhalb der Schilf-Pflanzen auf den gesamten CH_4-Fluss hat, und fanden einen zwischen 23% und 45% niedrigeren allgemeinen CH_4-Fluss, wenn Konvektionsströmung ausgeschlossen werden konnte, indem das Schilfrohr abgeschnitten, bzw. abgeschnitten und versiegelt wurde. Die Gasttransportwege von der Erde zur Atmosphäre veränderten sich ebenfalls. Der relative Beitrag der Ebullition zum allgemeinen Fluss stieg von 2% bei intaktem Schilfrohr auf 24-37% bei geschnittener Vegetation. Es ist deutlich, dass in unserem Plot der Anstieg von Ebullition nicht den verhinderten Gastransport durch die Konvektionsströmung kompensieren konnte. Das Experiment zeigte ebenfalls, dass der Transport von CH_4 durch Pflanzen, wobei die sauerstoffhaltige Wasserschicht umgangen wird, einen viel größeren Effekt auf die CH_4 Emission hat als die Änderung der CH_4-Oxidation und -Produktion in der Rhizosphäre durch den O_2 Transport durch die Pflanzen. Insgesamt zeigt dies, dass Pflanzen mit Konvektionsströmung Gastransport Mechanismen einen wichtigen Beitrag zur CH_4-Emission von Feuchtgebieten beitragen.

Insgesamt, war das Moor über das gemessene Jahr betrachtet eine Senke für Kohlenstoff und Treibhausgase, es wurden 221 g C m^{-2} yr^{-1} Kohlenstoff aufgenommen (26% des überhaupt assimilierten Kohlenstoffs). Die netto Aufnahme von Treibhausgasen betrug 52 g CO_2 eq.m^{-2} yr^{-1}, wobei 894 g CO_2 m^{-2} yr^{-1} CO_2 aufgenommen und 842 g CO_2-Äq. m^{-2} yr^{-1} CH_4 abgegeben wurde. Verglichen mit der langfristigen Aufnahme von Kohlenstoff in nördlichen Mooren (20–50 g C m^{-2} yr^{-1}) ist die Aufnahme von 212 g C yr^{-1} sehr hoch. Da die Auswertung der Messdaten eines Jahres keine belastbare Schlussfolgerung über den Einfluss dieses Moores auf den Klimawandel zulässt, sollte auch aus den anderen gemessenen Jahren (2014, 2016) die Kohlenstoffbilanz evaluiert werden.

Bezüglich der gemessenen ET hat unser Standort eine niedrige ET im Vergleich mit anderen *Phragmites* Feuchtgebieten im gemäßigten Klima. Besonders in Zeiten geringer Pflanzenaktivität (Mai und Oktober) war die ET sehr gering, der dominante Wärmefluss war der sensibele und nicht der latente Wärmefluss. Dies kann durch die große Menge an abgestorbenen Schilfrohrpflanzen in diesen Monaten erklärt werden, da sich das tote Schilfrohr dann erwärmt und einen hohen

sensiblen Wärmefluss verursacht. Verdunstung war aufgrund der Beschattung durch die Pflanzen und geringer Windgeschwindigkeiten entlang der Oberfläche niedrig. Während der Entwicklung von *Phragmites* stieg die Transpiration an und trug maßgeblich zu LE bei. Die Penman-Monteith Gleichung der FAO erwies sich als guter Schätzwert der gemessenen ET, „crop factors“ aus der Literatur verwendet wurden. Eine besonders gute Übereinstimmung ziwschen gemessener und berechneter ET, ergab das Regressionsmodel von Zhou und Zou (2009). Dieses Model verwendet Lufttemperatur, relative Luftfeuchtigkeit und netto Strahlung als Inputvariablen. Wahrscheinlich besteht hier ein Zusammenhang zum stomatären Widerstand, welcher auf denselben Variablen beruht. Aus diesem Grund ist das Model von Zhou und Zhou (2009) ein interessantes Werkzeug, um tägliche crop factors zu berechnen. Es ist außerdem robust genug, um in verschiedenen Regionen verwendet zu werden (China im Vergleich zu Deutschland). Insgesamt, betrug ET etwa die Hälfte des Niederschlags, wodurch das Risiko des Austrocknens des Feuchtgebietes nicht realistisch ist.

Chapter 1

General introduction

1.1 PEATLANDS IN A GLOBAL PERSPECTIVE

Peat soil is an organic sediment layer which consists of incomplete decomposed plant material. Since the soil is (partly) below water, anaerobe processes play an important role and total mineralization of the organic material does not take place. Mostly the structure of the plants is still visible. Although plant material is not totally decomposed, only 2-16 % of the primary production is stored in peat, leading to a growth of 0.2-2 mm yr^{-1} (Succow and Joosten, 2001). The rest of the primary production is set into carbon dioxide (CO_2) and methane (CH_4). The global carbon accumulation of peat soils adds up to 0.1 Gt-C per year. About one-third of the soil carbon is stored in peatlands (Gorham, 1991; Chesworth (ed.), 2007). On the one hand, peatlands accumulate carbon which is an interesting characteristic to (slightly) compensate the carbon emitted by fossil fuels (emission from fossil fuel is 9.5 Gt-C yr^{-1} (IPCC 2013: Stocker et al., 2013). On the other hand, peatlands are natural emitters of CH_4 (Reiche et al., 2010). Over a 100-year cycle, methane is a 28 times stronger greenhouse gas than carbon dioxide (IPCC 2013: Stocker et al., 2013) and is therefore an important factor for climate change. The net budget of greenhouse gases depends on the stage of formation of the peatland. In an early stage, peatlands have mostly a negative greenhouse effect while it turns slightly positive in an older stage when the peat layer is thicker (Chesworth (ed.), 2007).

The greenhouse gas budget is very different in disturbed peatlands. World-wide, many peatlands are disturbed by mining and drainage activities. With these disturbances, oxygen can reach the peat and the organic soil is decomposed to CO_2. This results in a CO_2 emission equal to 9-15% of the total emission globally (Kaat and Joosten, 2008). Since the 18th century, peat has been intensively excavated in Europe to be used as an energy source. About 19 million metric tons of peat have been used for this purpose (Mitsch and Gosselink, 2007). Today most of the mined peat is used as potting medium for horticulture and private gardening because of the porosity and water retention characteristics of peat. In 1998, Germany was the 4th largest peat producer in the world (after Finland, Ireland and Russia) (Mitsch and Gosselink, 2007). The amount of excavated peat in Germany, is still about 8 million cubic meter yr^{-1}, which is equal to 20.000 ha yr^{-1} (Presse- und Informationsamt der Bundesregierung, 2015). Peat drainage for the conversion into agricultural land is another cause for disturbance. Nowadays, this especially occurs in the tropics for palm oil cultivation, like in Indonesia (Kaat and Joosten, 2008). Even if drainage activities are reduced, the decomposing of peat still continues as long as the water table is low and oxygen can enter the soil. In Germany, the emission from disturbed peatlands is 30 million t CO_2 yr^{-1}, this equals around 5% of the national CO_2 emission (Kaat and Joosten, 2008; Moore BW, 2011). Therefore, conserving intact peatlands and restoring degraded peatlands is useful to

prevent further CO_2 emissions (Kaat and Joosten, 2008). The total greenhouse gas emission reduction that can be gained is around 1569 million t CO_2 equivalent yr^{-1} (Griscom et al., 2017; see Fig. 1.1).

1.2 METHANE PRODUCTION, OXIDATION AND EMISSION

Methane is an organic compound that is produced by microbes in anaerobic conditions. The

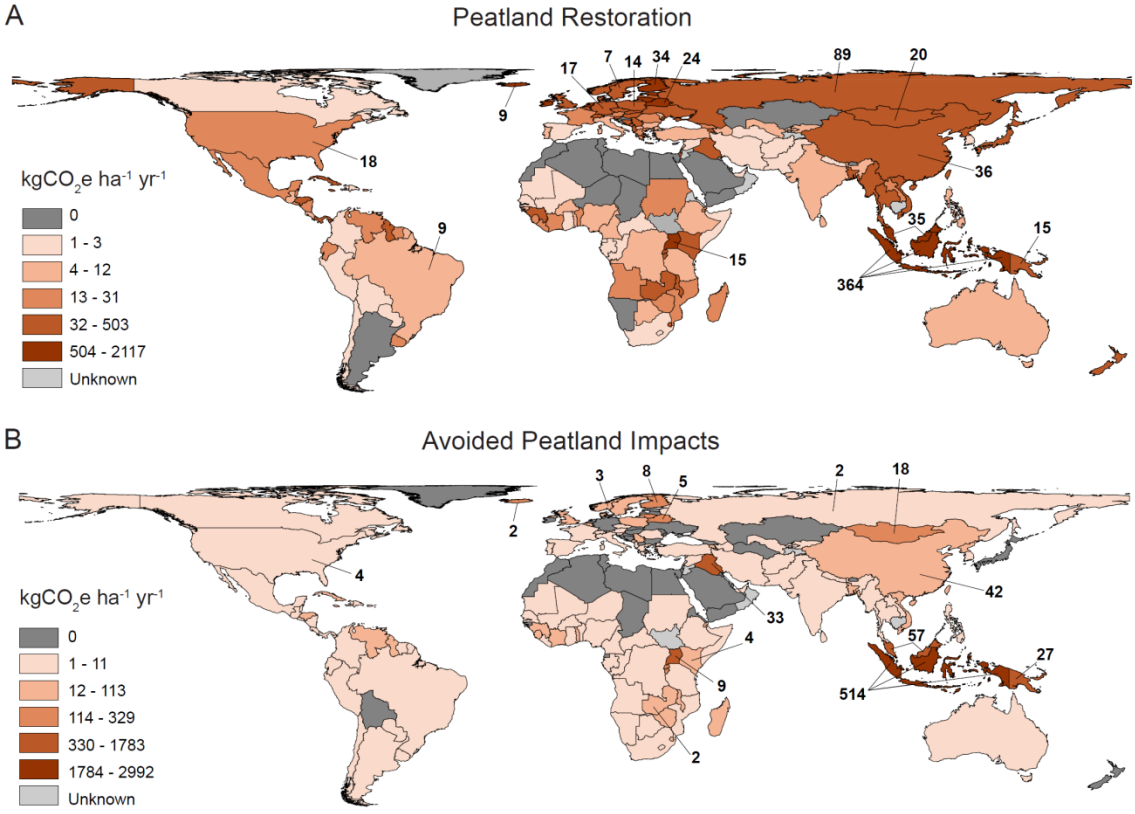

Fig. 1.1 Potential CO_2 mitigation in CO_2 equivalent (CO_2e) by peatland restoration (A) or avoided peatland impacts (B) per country. The single numbers present the total amount per country in Gt- CO_2e yr^{-1}. From Griscom, et al. (2017).

strong warming potential compared to CO_2 makes that anthropogenic CH_4 emission accounts for 16% of the total greenhouse gas emission in CO_2 equivalent (IPCC 2013: Stocker et al., 2013). In the atmosphere, CH_4 has a lifetime of around 10 years mainly due to the reaction with hydroxyl (OH) radicals in the troposphere ($CH_4 + OH\cdot \longrightarrow CH_3\cdot + H_2O$). Even with this relative short lifetime, the CH_4 concentration in the atmosphere is more than doubled compared to the pre-industrial level (in 2011 1800 ppb; IPCC 2013: Stocker et al., 2013), due to increase in number of domestic ruminants, use of fossil fuels, rice cultivation, waste decomposition and biomass burning (Wuebbles and Hayhoe, 2002). Wetlands (including peatlands) contribute 72% to the CH_4 emission from natural sources and account for 22% from all sources (natural and anthropogenic)

(Wuebbles and Hayhoe, 2002). Even though CH_4 emission from wetlands is not anthropogenic, there is still a great interest in understanding the mechanism behind the production, oxidation and emission of CH_4 from these ecosystems.

CH_4 production by methane producing micro-organisms (methanogens) depends on the amount of available substrate, redox conditions and temperature. Acetate is the most important substrate (in quantity) for methane production and is used by acetotrophic methanogens ($CH_3COOH \longrightarrow CH_4 + CO_2$). Acetate is produced by the breakdown of longer organic polymers by other micro-organisms (Fig 1.2). In this process, CO_2 and hydrogen gas (H_2) are produced as well. $H_2 + CO_2$ is the second most important substrate and is used by hydrogentrophic methanogens to produce methane ($4H_2 + CO_2 \longrightarrow CH_4 + H_2O$). Methanogenesis is sensitive to temperature, with a Q_{10} between 5.3 and 16 (Dunfield et al., 1993). It has its optimum between 25-35 °C and its minimum between 5-10 °C (Dunfield et al., 1993; Boon and Mitchell, 1995). Methanogens thrive with a redox potential lower than -200 mV. This occurs when oxidizing agents like oxygen, nitrate, iron(III) and sulfate are reduced. Water table height determines the oxygen level in the soil, therefore methane production will decrease with lowered water table (Moore and Knowles, 1989).

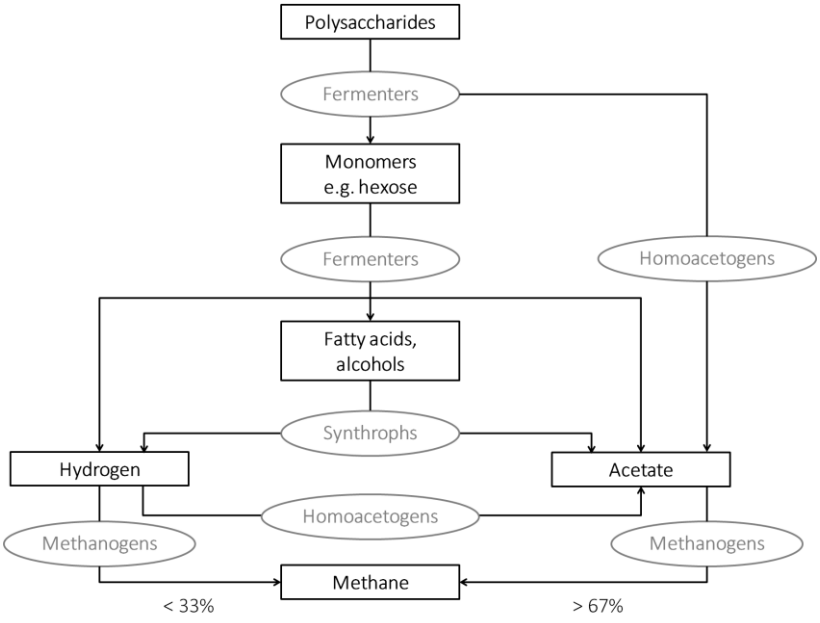

Fig. 1.2 Main pathways of methanogenesis. From Lai (2009).

Oxygen does not only limit CH_4 production, it also increases CH_4 oxidation. This process is carried out by methanotrophs ($CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$). CH_4 oxidation is the highest at the position of the water table (Bubier and Moore, 1994; van der Nat et al., 1997; Lai, 2009). Below the water table oxidation takes place in the rhizosphere due to oxygen transport by plants to their root system (see section 1.3.2). Vascular plants with aerenchyma tissue can also transport CH_4 from the soil to the atmosphere, bypassing the oxic soil layer. Besides the CH_4 transport by plants, CH_4 travels through the soil via diffusion and bubbles (ebullition) (Succow and Joosten, 2001). With diffusion, a larger part of the produced CH_4 is oxidized than with ebullition, due to the difference in transport velocity (diffusion is much slower). Vascular plants reduce the amount of ebullition, because they decrease CH_4 concentration in the rhizosphere due to CH_4 transport and CH_4 oxidation (Chanton, 2005).

Water table height and the presence of vascular plants highly influence CH_4 production and oxidation. A low water level and vascular plants gives the lowest amount of emissions, while high water table and vascular plants show the highest methane emission (Hendriks et al., 2010).

1.3 THE ROLE OF *PHRAGMITES* IN PEATLANDS

Phragmites australis (common reed) is a widely abundant helophyte species found on every continent on Earth. It is a perennial grass that can live in many habitat types like ditches, ponds, brackish marshes, estuaries and peatlands. Individual plants are connected with each other by rhizomes. The plant can spread via rhizomes and via seed production. *Phragmites* is often the first peat building species in peatlands that originated from alkaline lakes (Succow and Joosten, 2001).

1.3.1 CARBON CYCLING

The primary production of *Phragmites* is very high; it can be up to 10 kg dry mass m^{-2} (Brix et al., 2001). The amount of carbon from the primary production that is accumulated in the soil is very much site-depending. For a site in Denmark it was calculated that 47% of the assimilated carbon was accumulated and the rest was released as CO_2 (49%) and CH_4 (4%) (Brix et al., 2001). In a *Phragmites*-wetland, the methane production is related to the release of (labile low molecular-weight) organic compounds from the rhizomes during the growth season (van der Nat and Middelburg, 2000). During winter, temperature is the limiting factor (Brix et al., 2001).

1.3.2 PLANT-MEDIATED GAS TRANSPORT

Many wetland plants have the ability to transport gases through their stem via aerenchyma. This type of tissue is a special adaptation of wetland plants standing in flooded soils but emerging

above the water surface, building gas channels to transport O_2 to the roots. The gas channels enable gas diffusion between the roots and upper plant parts. Mostly more O_2 is transported to the roots than is consumed, leading to O_2 leakage into the rhizosphere. This leads to the effect that toxic components, like reduced iron, are oxidized in the soil around the growing part of the rhizome (Colmer, 2003). Different wetlands plants like *Phragmites australis* have developed an O_2 barrier to keep the oxygen in the roots for respiration (Soukup et al., 2006). The mature parts of the rhizome is relative impermeable for gases, but O_2 leakage occurs in the apices. The aerenchyma roots have relative large diameter to keep the surface small. Both the flooding induced O_2 barrier and the larger root diameter probably have the disadvantage that uptake of water and plant nutrients are less (Lambers et al., 2008). Besides oxygen transport in *Phragmites* to the soil, gases from the soil (CO_2 and CH_4) can be transported to the atmosphere

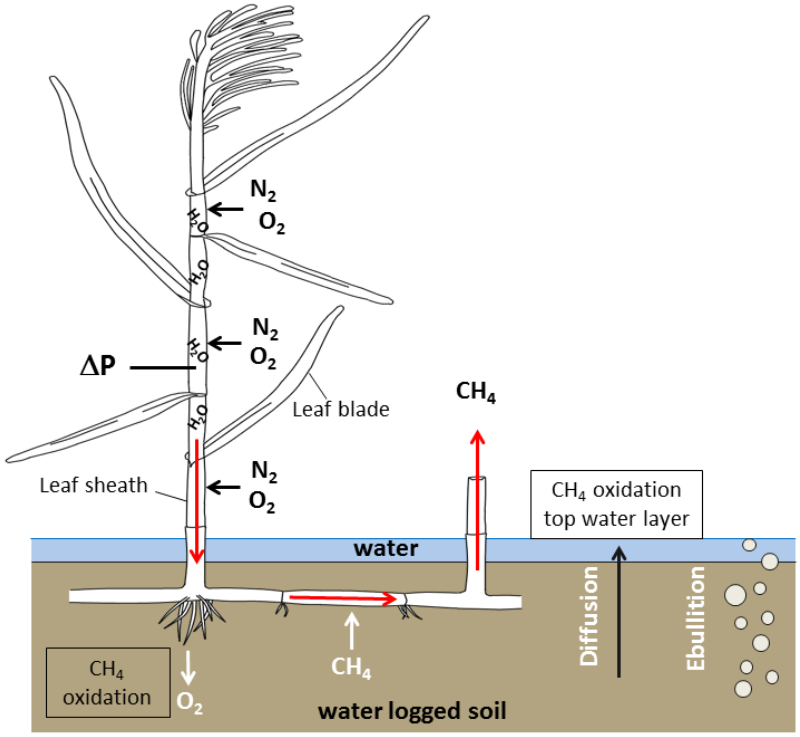

Fig. 1.3 Schematic overview of the humidity induced convection inside *Phragmites* plants. N_2 and O_2 are transported through stomata of the leaf sheath, following the diffusion gradient. A higher pressure inside the stem is created in living plants (ΔP), which creates an airflow towards the rhizome and goes back to the atmosphere via old or broken stems (red arrows). O_2 is transported to the soil and CH_4 that diffuses into the rhizome will be transported to the atmosphere. On the places where O_2 and CH_4 are present together, CH_4 oxidation occurs.

via aerenchyma (Lambers et al., 2008). CH_4 transport starts with the diffusion of CH_4 in the rhizosphere to the roots. From there CH_4 can be transported via the rhizome culm and stem culm to the atmosphere. During growing season (when living reed is present) the transport occurs by convective flow of air (Brix, 1989). The convective flow through the culm is created by humidity-induced pressure within the leave sheaths (part of the leave around the stem) (Fig. 1.3) (Armstrong and Armstrong, 1990, 1991; Armstrong et al., 1996; Afreen et al., 2007). This means that a pressure gradient arises due to the difference in humidity between the humid gas inside the culm and the relatively dry gas in the atmosphere (Armstrong et al., 1996). The pores in the leaf sheaths (and for a smaller part pores in the stem) are relative resistant against pressure differences. But the pores do transport gases that move due to diffusion. Because of the higher humidity in the internal gas, O_2 concentrations inside the plant becomes lower, therefore more O_2 is transported from the atmosphere into the sheaths and a higher pressure arises. The aerenchyma channels in the sheaths are connected with the pith cavity in the stem via nodes of the culm (Afreen et al., 2007). The higher pressure inside the sheaths creates an air flow through the whole stem and rhizomes, with the efflux from old broken stems (Armstrong and Armstrong, 1991). The higher the difference in humidity inside and outside the sheath, the larger the effect of the pressurized convection is. There is a linear correlation between atmospheric humidity decrease and humidity-induced convection (HIC) increase (Armstrong and Armstrong, 1991). The latent heat plays an important role as well, since it causes water to evaporate from the cells around the stomata. HIC starts after sunrise, has its optimum in the early afternoon and decreases till the sun is set (Brix et al., 2001). During the night, the stomata are closed and energy input is reduced, which results in reduced air flow within the stem. The concentration of CH_4 rises in the stem, in both influx and efflux culms, by diffusion. Just before sunrise, the CH_4 concentration can be up to 1000 times higher than during midday in the influx column (Chanton et al., 2002). When the HIC starts after sunrise, the CH_4 is flushed out from the influx culm and the concentration of CH_4 in the efflux culm is higher than in the influx culm (Brix et al., 2001). Flow rates induced by HIC of around 10 mL min^{-1} are observed in *Phragmites australis* (Chanton et al., 2002). During nights with winds, a “venture-induced” convective flow can be created (Brix et al., 1992).

This HIC influences the amount of CH_4 oxidation in the rhizosphere and the transport pathway of CH_4 from the soil to the atmosphere. The relative high amount of methane oxidation in *Phragmites*-dominated peatlands (20-70%) is due to the O_2 release by the roots (Brix et al., 2001). At the same time, in this type of peatlands, 70% of produced methane is transported through the plants (Brix, 1989). That is why it is important to study the impact of this mechanism on the CH_4 emission (see chapter 2 and 3).

1.3.3 EVAPOTRANSPIRATION

The characteristics of a peatland largely depend on the hydrology of the system (Succow and Joosten, 2001). Rainfall and evapotranspiration are dominating factors of the water balance of a wetland. In general, wetland plants can transpire much since they experience no water limitation. *Phragmites* is expected to have a high evapotranspiration rate due to the large leaf area, open water habitat and high aerodynamic roughness (Acreman et al., 2003). There is evidence from literature that evapotranspiration from reed areas could exceed open lake evaporation (Burba et al., 1999; Herbst and Kappen, 1999) and even the yearly precipitation (Herbst and Kappen, 1999), which could eventually cause drying out of a wetland. It is therefore relevant to measure evapotranspiration from a *Phragmites*-system to get a better understanding of driving forces behind it (see chapter 4).

1.4 ORIGIN OF THE PEATLAND ´FEDERSEE-MOOR'

The ´Federsee-Moor´ is a terrestrialisation mire of 30 km^2, developed by the natural declining of a proglacial lake, which is typical for peatlands north of the Alps. It is located in the region ´Upper Swabia', 50 km north of the Lake Constance and 10 km southeast of the Danube valley. The wider area is characterized by its morainic landscape, which forms the origin of the Federsee basin.

In the time the Alps were formed, about 1 million years ago, a reduction area arose north of the mountain chain. During the Pleistocene, the basin of the Federsee was shaped by glaciers from the Alps that covered a large area of the alpine foothills during ice ages, especially during the 'Rißeiszeit' (second last ice age). In the 'Würmeiszeit' (last ice age), the average temperature was higher than in the large ice ages before, causing a smaller area of glacier cover. At the end of this period (30.000 years ago) the Federsee basin was closed in the south by depositions of the retreating glacier (Grüttner et al., 1996). What remained was a 30 km^2 proglacial lake. The size of the lake declined to 11 km^2 after the last ice age because of natural terrestrialisation due to the accumulation of minerals and organic material. Further declining occurred between 1787 and 1808, when the lake was drained for agricultural purposes. Since the beginning of the 19th century the lake size was 1.4 km^2 (Günzl, 2007).

The development of the lake can be traced back in the soil layers. The oldest layer developed during the ice age when mineral particles came from the glacier into the lake and were deposited on the bottom. This forms the deepest soil layer called Clay gyttja. Due to the lack of biological activities in this period, there is no organic material found in this layer. With better climate conditions after the ice age, humans started to settle around the lake. In the lake itself life occurred in the form of phytoplankton. Its amount increased rapidly, which caused a decline of

CO_2 in the water that resulted in lime deposition from the lime rich water. A layer of 1 to several meters of Lime gyttja developed. Oxygen concentration was reduced due to the stronger biological productivity and low oxygen circumstances arose at the bottom of the lake, with the consequence that detritus from algae was hardly broken down. The sediment's consistency that developed, Liver gyttja, is dark and elastic. In the shallow areas at the sides of the lake reed (*Phragmites australis*) beds developed. The first Reed peat developed from plant material that could not be broken down. When the soil was elevated to average water level, fen vegetation (*Carex*, mosses) took over the reed vegetation. Due to further peat building the peat soil grew above the water level. This resulted in a local elevated groundwater table that was for a large part fed with rainwater. The peatland became more attenuated with low nutrients. This was the start of the development of a peat bog with Peat moss (*Sphagnum*), Pod grass (*Scheuchzeria*) and Cotton grass (*Eriophorum*) as vegetation (Grüttner et al., 1996). Peat development as described above is not the same for every part of the Federsee-Moor. Peat bog, for example, has only developed in the southern area. But due to intensive excavation between 1850 and 1960, hardly anything of the peat bog has remained (Günzl, 2007). The soil of the newly gained land by the drainage activities 200 years ago differs from the peat bog soil: Peat there consists only of young reed peat which is directly above the gyttja without a transition zone. This is the area where the studies of chapter 2-4 were conducted.

The variety of vegetation type within the Federsee-Moor is mainly influenced by current or

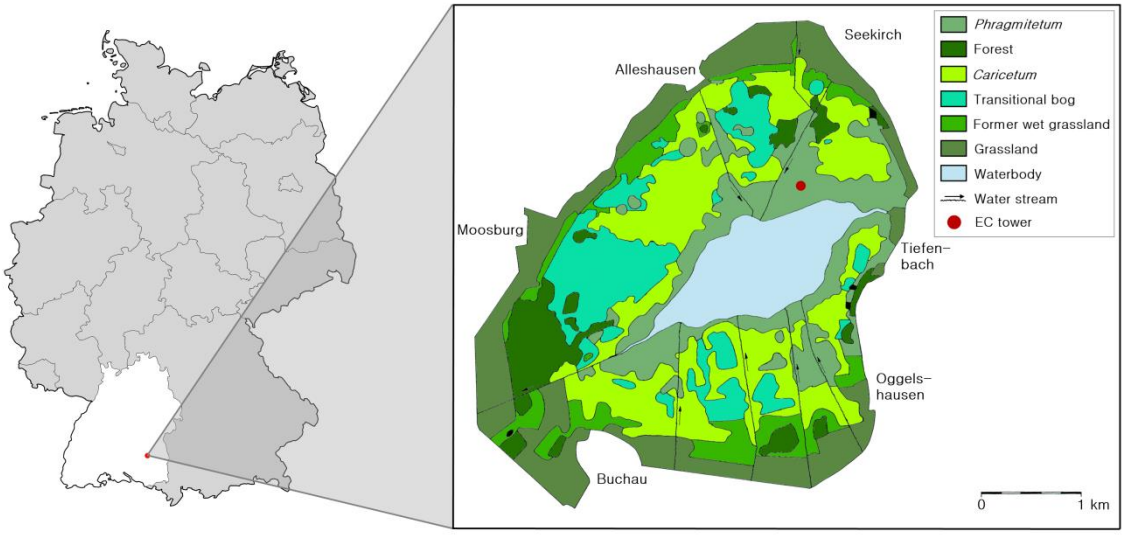

Fig. 1.4 Vegetation cover of a part of the nature protection area Federsee. This area is the 14 km^2 which was the gained land from drainage activities 200 years ago. In the middle of the *Phragmitetum* area (at EC tower) the studies of chapter 2, 3 and 4 were conducted. Adapted from Grüttner et al. (1996).

former human activities. Before the lake's declining more 200 years ago, the area around the lake was used as pastures and to produce cattle feed and straw (Günzl, 2007). The newly gained land

was used for the same purposes but appeared to be not profitable because of the very high groundwater table. The decreased land management led to a high variety of vegetation types like forest, grassland and communities of *Phragmitetum* and *Caricetum* (see Fig. 1.4). This area, of around 14 km^2, contains the most natural vegetation of the Federsee-Moor and became a nature protection area in the beginning of the 20th century (Grüttner et al., 1996). The protected area was expanded throughout the years to the current size of 23 km^2. The expanded area includes mainly grasslands, but also the last remained peat bog and forests with among others Mountain Pine (*Pinus mugo*).

In the middle of the *Phragmitetum* (reed) area, the studies of chapter 2, 3 and 4 were conducted.

1.5 THE EDDY COVARIANCE METHOD

With the Eddy Covariance (EC) method, the net vertical flux of matter (e.g. CO_2 and CH_4) and heat (latent and sensible) between land surface and atmosphere is quantified by calculating the covariance between the fluctuation of vertical wind and of the density/concentration of the matter of interest (Aubinet et al., 2012), on the assumption that all transport of matter and heat occurs via turbulence flow. A turbulence flow is in general hard to predict due to its stochastic, non-linear character (Rogallo and Moin, 1984) and exists of eddies on all kind of scales (see Fig. 1.5). An eddy is a pattern determined by velocity, vorticity and pressure. Horizontal wind flow consists of many eddies and the lower to the ground the smaller the eddies are (Burba and Anderson, 2005-2010). Smaller eddies rotate with a higher frequency.

Measurements are mostly made in the surface boundary layer where the dominant transport mechanism is atmospheric turbulence (Aubinet et al., 2012). This layer is usually twice the canopy height, with a minimum of 1.5 m. The velocity and direction of eddies are measured with a sonic anemometer (horizontal and vertical wind speed) and its density/concentration of the matter of interest with gas analyzers (in our case CH_4 and CO_2/H_2O). The measurement frequency is usually 10 Hz, thus eddies which rotate with a higher frequency are not detected. The shape of the gas analyzer also determines the minimum size of the eddies that are measured. With these high frequency wind and gas concentration data, fluxes are calculated over a certain period, usually 30 minutes.

The source area from where the measured gas concentration originates from is called the footprint of the flux (Aubinet et al., 2012). Close to the tower there is hardly any contribution to the measured fluxes. A peak can be located between a couple of times the measuring height to a few dozen time (depending on the amount of turbulence, atmospheric stability etc.) (Aubinet et al., 2012). The flux footprint increases as measurement height increases, when surface roughness

decreases and when atmospheric conditions change from unstable to stable (Burba and Anderson, 2005-2010).

The quality of the flux measurement is largely depending on corrections that are applied (Foken, 2008a). Some of these corrections are: time lag compensation for the distance between the anemometer and gas analyzers, correction of the tilt of the anemometer, and compensation for fluctuations in water vapor and heat, which affects the air density (Webb et al., 1980).

A quality check for the EC fluxes is the energy balance. It is expected that the total available energy, net radiation (Rn) – ground heat flux (G), is partitioned into the turbulent heat fluxes, sensible heat flux (H) and latent heat flux (LE). In most cases however, there is an imbalance, whereby (Rn – G) > (H + LE) (Foken, 2008b). Neglecting the minor fluxes and the storage terms, the missing energy may be uncaptured LE or H fluxes or both. If LE is underestimated, CO_2 and CH_4 fluxes are probably underestimated as well. This imbalance is a longstanding problem and a well-known source of uncertainty in EC measurements.

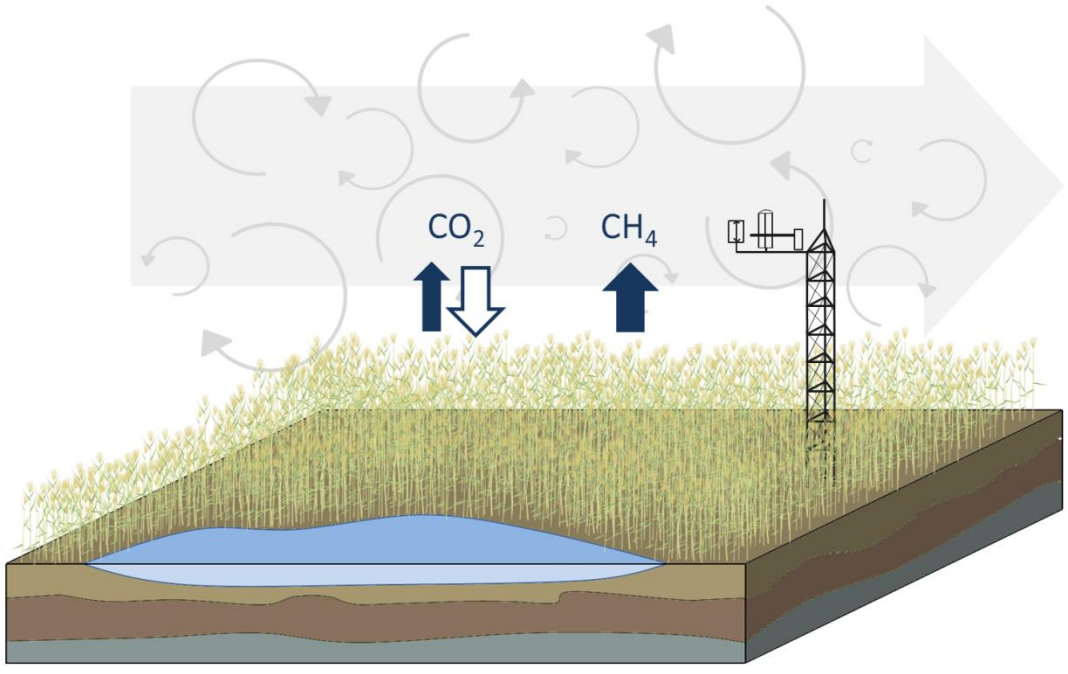

Fig. 1.5 Schematic overview of captured CO_2 and CH_4 fluxes from the reed area of the Federsee-moor, by means of the eddy covariance method.

1.6 RESEARCH AIM

In Germany, about 90% of the peatlands have been drained or are otherwise disturbed. It is estimated that this causes 5% of Germany's total greenhouse gas emissions (Moore BW, 2011). Action is taken by the Council of Environmental Advice (Sachverständigenrat für Umweltfragen) by protecting intact peatlands and rewetting areas that are able to function as a carbon sink. Above that, the national Biodiversity Strategy (Biodiversitätsstrategie) has the aim to increase carbon storage capacity by restoring 10% of the peatlands in Germany by 2020. Every German federal state has to develop its own strategies to reach this target (Moore BW, 2011). Since there is a lack in reliable data, the federal state of Baden-Württemberg wanted to acquire an overview of the carbon cycle of peatlands so that future management decisions can be based on this knowledge. To fill the knowledge gaps, the EmMo project ("Repräsentative Erfassung der Emissionen Klimarelevanter Gase aus Mooren Baden-Württembergs") was initiated in 2012. Three peatlands in Baden-Württemberg were selected to monitor greenhouse gas fluxes. One of the peatlands was the Federsee-Moor in Oberschwaben. We were responsible for establishing a carbon budget for the low disturbed reed area in the Federsee-Moor.

CO_2 and CH_4 fluxes from the ecosystem into the atmosphere and back were measured with the EC method (see section 1.5 and Fig. 1.5). With continuous measurements over a long time period and large contributing area, the method yields the most precise data on surface exchange which is currently available. This is a big advantage compared to the traditional closed chamber method, where the measurements are limited in time and space (Myklebust et al., 2008; Schrier-Uijl et al., 2010).

Besides creating a carbon budget for this ecosystem, a better understanding in the influencing factors on the fluxes is of large interest. A further central aim was to find out how the plant-mediated gas transport of *Phragmites* (HIC) influences CH_4 emission. This was done by analyzing the EC flux data and by relating the fluxes to environmental variables (chapter 2) and with a field experiment, where the effect of excluding HIC (by cutting the plants) on the CH_4 emission was studied (chapter 3).

With the EC data it was also possible to determine the total evapotranspiration of this peatland. *Phragmites*-wetlands are expected to have a high evapotranspiration rate (see section 1.3.3), which could highly influence the hydrology of the system. The accumulation of organic material occurs because of the limiting oxygen levels and hydrological processes are therefore fundamental in the development of peatlands. That is why it is relevant to quantify the evapotranspiration from this peatland.

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Chapter 2

The role of *Phragmites* in the CH_4 and CO_2 fluxes in a minerotrophic peatland in southwest Germany

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Abstract

Peatlands are interesting as a carbon storage option, but are also natural emitters of the greenhouse gas methane (CH_4). *Phragmites* peatlands are particularly interesting due to the global abundance of this wetland plant (*Phragmites australis*) and the highly efficient internal gas transport mechanism, which is called humidity-induced convection (HIC). The research aims were to (1) clarify how this plant-mediated gas transport influences the CH_4 fluxes, (2) which other environmental variables influence the CO_2 and CH_4 fluxes, and (3) whether *Phragmites* peatlands are a net source or sink of greenhouse gases. CO_2 and CH_4 fluxes were measured with the eddy covariance technique within a *Phragmites*-dominated fen in southwest Germany. One year of flux data (March 2013–February 2014) shows very clear diurnal and seasonal patterns for both CO_2 and CH_4. The diurnal pattern of CH_4 fluxes was only visible when living, green reed was present. In August the diurnal cycle of CH_4 was the most distinct, with 11 times higher midday fluxes (15.7 mg CH_4 m^{-2} h^{-1}) than night fluxes (1.41 mg CH_4 m^{-2} h^{-1}). This diurnal cycle has the highest correlation with global radiation, which suggests a high influence of the plants on the CH_4 flux. But if the cause were the HIC, it would be expected that relative humidity would correlate stronger with CH_4 flux. Therefore, we conclude that in addition to HIC, at least one additional mechanism must be involved in the creation of the convective flow within the *Phragmites* plants. Overall, the fen was a sink for carbon and greenhouse gases in the measured year, with a total carbon uptake of 221 g C m^{-2} yr^{-1} (26% of the total assimilated carbon). The net uptake of greenhouse gases was 52 g CO_2 eq.m^{-2} yr^{-1}, which is obtained from an uptake of CO_2 of 894 g CO_2 m^{-2} yr^{-1} and a release of CH_4 of 842 g CO_2 eq.m^{-2} yr^{-1}.

2.1 INTRODUCTION

Approximately one-third of the world's soil carbon is stored in peatlands, although they cover only 3% of earth's total land surface (Lai, 2009). Therefore, peatland conservation or restoration as a climate change mitigation option has recently gained much attention (Bonn et al., 2014). Apart from the positive effect of carbon storage, peatlands are also natural emitters of methane. Methane is a 28 times stronger greenhouse gas than carbon dioxide when calculated over a 100-year cycle (IPCC, 2013). Estimates of methane emissions from peatlands range between 30–50 Tg yr^{-1} worldwide (Roulet, 2000). There is a high variation in methane emissions. This variability, however, and all underlying processes are not yet well understood (Hendriks et al., 2010; Segers, 1998). It is therefore essential to gain more knowledge about the role of methane in the greenhouse gas budgets of peatlands.

In wetland ecosystems, methane can be transported from the soil to the atmosphere via diffusion, ebullition and via aerenchyma of roots and stems of vascular plants (Moore, 1994; Le Mer and Roger, 2001; Hendriks et al., 2010). The largest part of the methane produced in peatlands is directly oxidized in the soil (Le Mer and Roger, 2001; Brix et al., 2001; Lai, 2009). The extent of oxidation depends on the gas transport pathway and is highly dependent on the position of the water table (Moore, 1994; Le Mer and Roger, 2001; Brix et al., 2001; Lai, 2009) and the presence of vascular wetland plants (Grünfeld and Brix, 1999; Hendriks et al., 2010). Compared to other wetland plants, *Phragmites australis* (common reed) appears to have a high ability in transporting gases between the soil and atmosphere (Salhani and Stengel, 2001). The gas exchange within *Phragmites* plants takes place via convective flow through the culm. Currently, it is believed that this transport originates from creating a humidity-induced pressure gradient between the internal culm and the atmosphere (Armstrong and Armstrong, 1990, 1991; Armstrong et al., 1996b; Afreen et al., 2007). The pores (stomata) in the leaf sheaths of *Phragmites* are more resistant to pressure flow than against gas diffusion. Due to the higher humidity in the internal culm of the reed, O_2 and N_2 concentrations inside the plant are diluted. Therefore, O_2 and N_2 are transported along the concentration gradient from the atmosphere into the sheaths and a higher pressure is created. This causes an airflow from the green living reed stems to the rhizomes and goes back to the atmosphere via dead or broken stems that are still connected to the rhizomes. This mechanism is more than 5 times as efficient as diffusion (Brix et al., 2001) and is also found in other wetland plants (e.g. *Nuphar*, *Eleocharis*, *Nelumbo* and *Typha*) that have a submerged rhizome system (Dacey and Klug, 1979; Dacey, 1987; Brix et al., 1992a; Bendix et al., 1994). In a *Phragmites*-dominated wetland, 70% of the methane produced is transported through the plants (Brix, 1989). This means that methane emissions should be highly

dependent on this transport mechanism. Apart from this potential influence of humidity-induced convection (HIC) on methane fluxes, *Phragmites* wetlands can also accrete large amounts of carbon in the soil due to the high annual primary production compared to other wetland plants (Brix et al., 2001; Zhou et al., 2009).

Several studies on methane emissions (Kim et al., 1998a; van der Nat and Middelburg, 2000) and CO_2 emissions (Zhou et al., 2009) from *Phragmites*-dominated wetlands have been published. Most of them used the closed chamber method. Despite *Phragmites australis* being the most abundant wetland species on earth, to date, the eddy covariance EC) technique has only been used at two study sites: Kim et al. (1998a) performed CH_4 flux measurements in a fen in Nebraska, USA, and Zhou et al. (2009) measured CO_2 fluxes from a *Phragmites* wetland in northeast China. To our knowledge, EC CO_2 and CH_4 flux data from European *Phragmites* wetlands does not exist. To contribute to a better understanding of the role of *Phragmites* on CH_4 and CO_2 fluxes, flux measurements were taken in the minerotrophic peatland "Federseemoor," located in southwest Germany. With the EC method, we were able to measure the net ecosystem exchange of CH_4 and CO_2 in high temporal resolution. This made it possible to detect the influence of the plant-mediated gas transport of *Phragmites* on the CH_4 fluxes and to evaluate the role *Phragmites* peatland plays in climate change. We recorded diel and seasonal variation of these fluxes, evaluated the impact of environmental variables on the fluxes, and determined the carbon and greenhouse gas budgets of this ecosystem. In this paper, we present the results from a measurement period of 1 year, from March 2013 to February 2014.

2.2 Materials and methods

2.2.1 Study site

The study was conducted in the Federseemoor (48.092° N,9.636° E), a peatland with an area of 30 km^2 that is located in the Upper Swabia region, southwest Germany. This region is characterized by its moraines and is located on the edge of a high-rainfall zone due to the Alps. Therefore, with yearly precipitation of around 800 mm and an average temperature of 7.1 °C, the area is wetter and colder than the average for Germany. The Federseemoor developed by natural terrestrialization from a proglacial lake measuring 30 km^2 which was formed after the last ice age. The lake diminished to a size of 12 km^2 and was surrounded by fen and bog. Between the years of 1787 and 1808, the lake size was further reduced by drainage activities to a size of 1.4 km^2. The resulting 11 km^2 of reclaimed land was meant for agricultural purposes, but appeared to be unprofitable. Natural vegetation started to develop and today it is a nature conservation area, mainly consisting of fen but also transitional bog and wooded swamp.

The Federsee is completely surrounded by *Phragmites* vegetation, with a total area of 2.2 km^2 and a density of approximately 70 living shoots per m^2. To the northeast of the lake, in the middle of the reed, an EC tower was constructed (Fig. 1.4 and Fig. 1.5).

2.2.2 FIELD MEASUREMENTS

The location of the EC tower was selected so that only reed vegetation was within a 200 m distance of the tower (the potential footprint). An LI-7700 open-path CH_4 gas analyzer (LI-COR Inc., USA), an LI-7200 enclosed CO_2/H_2O gas analyzer (LI-COR Inc., USA) and a WindMaster Pro ultrasonic anemometer (Gill Instruments Ltd., UK) were installed at a height of 6 m, twice as high as the reed canopy. Molar mixing ratio, mass density of the gases and wind speed in three directions were measured at a frequency of 10 Hz. The LI-7700 is able to detect concentrations of up to 50 ppm CH_4 and was calibrated by the manufacturer for the concentration range 0–40 ppm CH_4 in June 2012. The LI-7200 was calibrated by the manufacturer up to 740 ppm in July 2012. The random error of the CH_4 flux computed by the EddyPro software (see Sect. 2.2.3) was around 15 %, and 20% for CO_2 flux.

Air temperature and relative humidity (HMP155, Vaisala Inc., Finland) as well as incoming and outgoing shortwave and longwave radiation (CNR4, Kipp & Zonen BV, the Netherlands) were measured at a height of 6 m. Soil temperature was measured at 5, 15 and 30 cm depths (LI-COR Inc., USA). The groundwater table was continuously measured with a groundwater data logger (Mini-Diver, Eijkelkamp Agrisearch Equipment BV, the Netherlands). Rainfall (TR-525USW, Texas Electronics Inc., USA) was measured above the canopy (at a height of 3 m). These environmental variables were measured every minute, except the water table height which was measured every 30 min. Vegetation height was measured weekly.

2.2.3 FLUX COMPUTATION

Fluxes from 1 March 2013 to 28 February 2014 were calculated with an averaging interval of 30 min using the software EddyPro version 5.1 (LI-COR Inc., USA). With this software, corrections are applied to average wind directions and gas concentrations and fluxes.

The declination of the angle-of-attack, caused by the shape of the anemometer, was corrected according to Nakai and Shimoyama (2012). To correct the tilt of the anemometer or angle of the mean horizontal wind, the double rotation method was applied (Wilczak et al., 2001). To convert from CH_4 mass density to molar concentrations, data were compensated for density fluctuations due to changes in water vapor and temperature (Webb et al., 1980). This does not apply to CO_2/H_2O gases since the temperature and pressure are constantly maintained in the enclosed-path gas analyzer. Therefore, mixing ratios were used for the flux calculation. The calculated fluxes were checked for quality by means of the 1–9 flagging system of Foken et al. (2004). Only

fluxes with quality flags 1–6 were used for further data processing. Outliers were filtered out by removing fluxes that were more than 4 times the median within a time window of 6 h and with six or more data points within this time window. Because of the often low turbulent conditions and stable stratification during the night, night fluxes with an average friction velocity < 0.15m s^{-1} were not considered in the data analysis.

After analyzing the footprint, it appeared that all fluxes were within a 200 m distance of the tower. The distance of the flux is an output of EddyPro using the method by Kljun et al. (2004), with the criteria that 90% of the measured gas concentration has its source within that distance. This means that only reed vegetation is within the measured footprint.

2.2.4 Gap filling

Due to technical failures and discarding data because of flux quality criteria, 46% of the CH_4 data and 35% of the CO_2 data were not present. Gaps were filled with the online tool provided by the Max Planck Institute for Biogeochemistry in Jena, Germany (http://www.bgc-jena.mpg.de/~MDIwork/ eddyproc/). This tool uses the look-up table method described by Falge et al. (2001) and Reichstein et al. (2005). This method was developed to fill CO_2 flux gaps. It uses the correlation of CO_2 fluxes with meteorological variables such as global radiation, ambient temperature and vapor pressure deficit.

To date, there is no established gap filling method for CH_4. Nevertheless, we found clear correlations between CH_4 fluxes and global radiation, temperature and relative humidity in our data. Therefore, we used the same gap filling method for CH_4 as for CO_2.

In the case of power or data logger failure, meteorological data were taken from a meteorological station run by the Federal State of Baden-Württemberg (LUBW) at a 2.2 km distance from the EC station.

Even with these data, the online tool still lacked sufficient data to properly fill a 2-month data gap that was caused by insufficient solar power within the time period 24 November 2013–30 January 2014. This was due to the maximum time window (14 days) that the tool uses. Therefore, a look-up table was made manually to fill this data gap. Global radiation classes with an interval of 100 W m^{-2} (from 0 to 800 W m^{-2}) and ambient temperature classes with an interval of 4 °C (from -10 to 18 °C) were created. For every combined class of temperature and global radiation, the average flux was used from the available data from November and February with the same class. Gaps in the look-up table were filled by linear interpolation. To estimate how reliable these gap-filled data were, an artificial gap was created for the month of May and was filled based on a look-up table created with data from April. The difference between observed and estimated data was on

average +30 %. Therefore, data from the filled gap of December–January are only used for the annual carbon budget estimation, but not for statistical analyses.

2.2.5 SEPARATING NET ECOSYSTEM EXCHANGE

The CO_2 fluxes measured with EC are the net ecosystem exchange (NEE). By definition, this is the gross ecosystem production (GEP) minus the ecosystem respiration (R_{eco}). Separating R_{eco} and GEP from NEE is done by using a simplified form of the regression model by Lloyd and Taylor (1994; Eq. 2.1) which describes the relation between respiration and temperature. The Q_{10} value was derived by a regression of the average CO_2 night flux (R_{eco}) on the average night soil temperature (T in °C) for every 2 months (more or less the duration of the different plant development stages) over the vegetation period (March–October):

$$R_{eco} = R_0 * Q_{10}^{T/10} \quad (2.1)$$

R_0 is the respiration when T is equal to 0. Only average night fluxes with six or more data points were considered and night is determined as the period where global radiation < 10 W m^{-2}. The

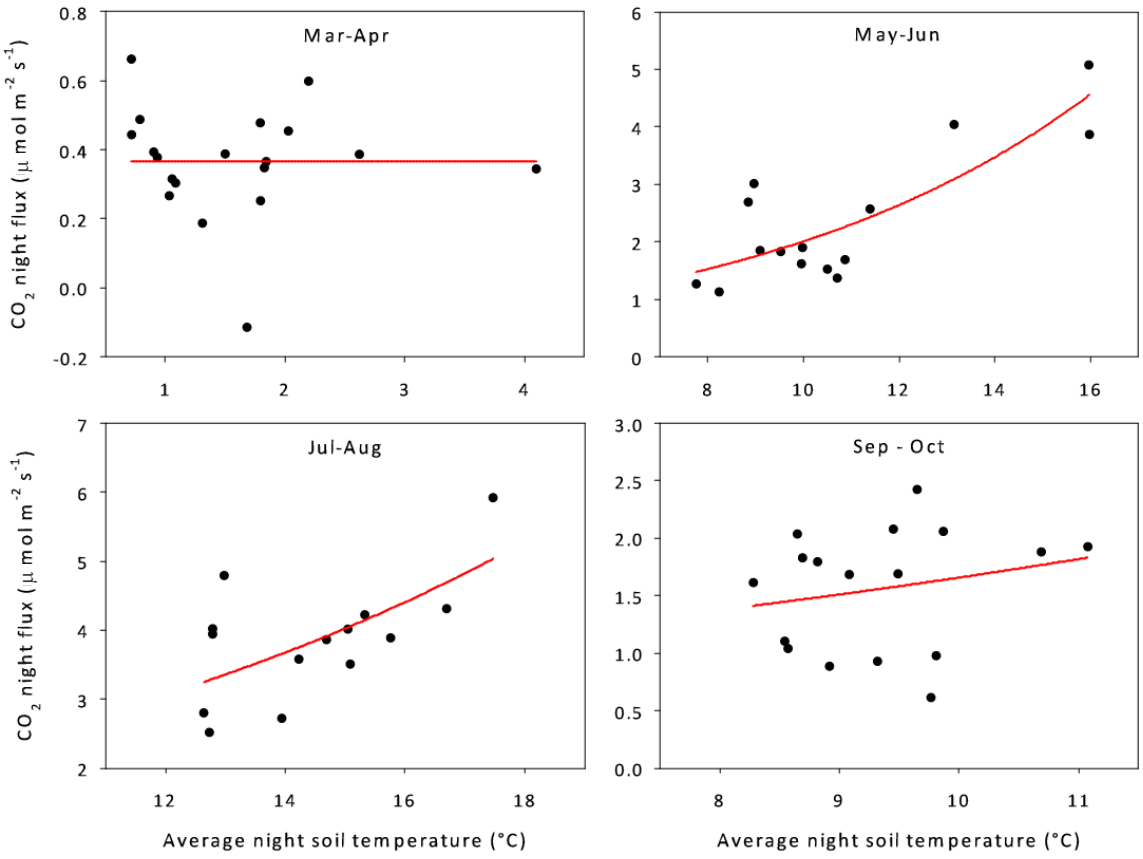

Fig. 2.1 Average CO_2 night fluxes for every 2-month period during the growing season plotted against average night soil temperature (black dots) with the regression model outcome (red lines).

Q_{10} values of the R_{eco} obtained (between 1.53 and 3.93; see Fig. 2.1) were used to calculate the R_{eco} for every half hour during the day within the vegetation period. This was done by using the

average CO_2 night flux as the reference respiration (R_{ref}) and the corresponding average night temperature as reference temperature (T_{ref}). The difference between T_{ref} and the daytime temperature was used to calculate the difference between R_{ref} during daytime R_{eco}. The GEP was then calculated by subtracting R_{eco} from NEE for every half hour during the day. The only period in which we found no dependency between CO_2 night fluxes and soil temperature was March–April. This is very likely to be due to the low soil temperature during this period (mostly below 4 °C). For these 2 months, daytime respiration was estimated by taking the average night CO_2 flux from that same day.

2.2.6 Statistics

Biserial (Pearson's) and partial correlation coefficients were calculated to explore the relationship between measured gas fluxes and environmental factors. For this we used the data at half-hourly resolution. Because the samples are autocorrelated in time and hence not independent, no confidence intervals were inferred and correlation coefficients were interpreted solely in a descriptive manner.

The impact of environmental factors on the gas fluxes was analyzed by polynomial regression models, making it possible to also model nonlinear relationships between environmental factors and gas fluxes. Because of the autocorrelative structure of the data, the regression models were made with the ARIMA (autoregressive integrated moving average) Box–Jenkins modeling approach. To achieve stationarity (constant expectation and variance) all data (gas fluxes and potential regressor variables) were differenced prior to the analysis. For the ARIMA analysis we used the daily averaged data measured in the vegetation period from 14 May to 31 October.

All statistical analyses were performed with the software PASW Statistics for Windows, Version 18.0 (SPSS Inc., released in 2009).

2.3 Results

2.3.1 Seasonal pattern in gas fluxes and environmental variables

The daily averages of CO_2 and CH_4 fluxes are presented in Fig. 2.2 together with the most important environmental variables. Only data until 25 November 2013 are shown because of the large amount of missing data after this date. The Northern Hemisphere's seasonal pattern is clearly visible in temperature and global radiation. These variables show the highest values in July, with average air and soil temperatures of 19 and 14 °C, respectively, and daily-averaged global radiation of 278 W m^{-2}. During the whole year, the water table never dropped below the soil surface, which means that the soil was water-saturated for the whole time.

The increase of temperature and global radiation at the beginning of the season initiated reed growth, starting by 30 April. From May, the reed plants assimilated CO_2 and daily CO_2 fluxes became clearly negative. At the same time, CH_4 fluxes rapidly increased. With green reed present, both CO_2 and CH_4 daily fluxes mainly follow global radiation (see Sect. 2.3.3) but in an inverse manner. This suggests a high influence of the vegetation on both fluxes. The highest CO_2 fluxes were measured in July, the month with the highest temperatures and maximum reed height (260 cm). In July, the average flux was -17.5 g CO_2 m^{-2} d^{-1}. The highest fluxes of CH_4 were measured in August, with an average of 0.151 g CH_4 m^{-2} d^{-1}. From early October, when the reed entered the senescence stage, fluxes became smaller (CO_2 positive) and on average there was no longer any uptake of CO_2. The lowest fluxes were measured in winter (November–February, data not shown), with an average release of 2.72 g CO_2 m^{-2} d^{-1} and 0.044 g CH_4 m^{-2} d^{-1}.

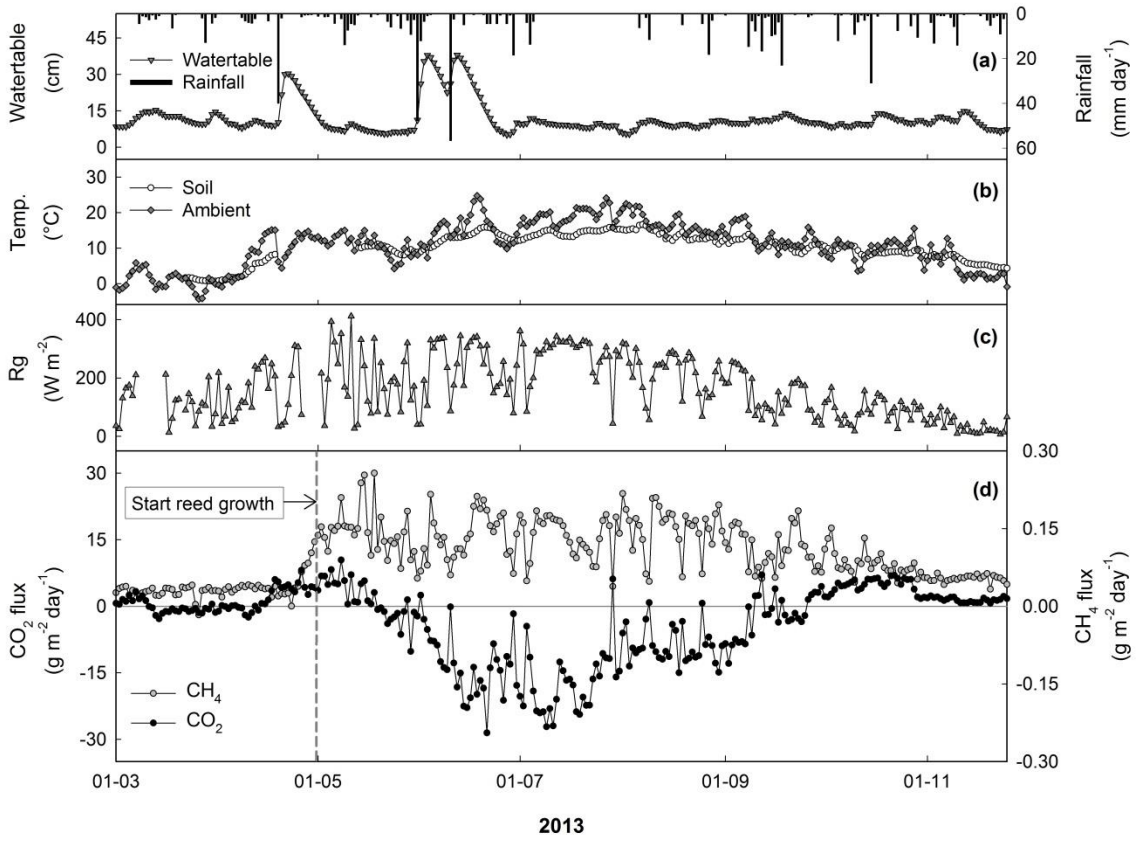

Fig. 2.2 (a) Daily averages of water table and rainfall, (b) soil and ambient temperature, (c) global radiation (Rg) and (d) CO_2 and CH_4.

2.3.2 DIURNAL PATTERN

To see how diurnal cycles of both CO_2 and CH_4 fluxes change over the season, the monthly-averaged diel fluxes of both gases are presented in hourly resolution (Fig. 2.3). CO_2 shows a weak diurnal pattern in the months of March and April, while there is no clear pattern visible for CH_4.

From May onwards, when new reed was present, a distinct diurnal pattern was established for both gases, with the highest negative fluxes for CO_2 and highest positive fluxes for CH_4 between 10:00 and 13:00. Over the whole growing season, the daily maximum for CH_4 and CO_2 flux was on average 15 and 30 min, respectively, earlier than the radiation maximum. The highest midday–night difference for CH_4 was observed in August with, on average, a midday flux of 15.7 and a night flux of 1.41 mg CH_4 m^{-2} h^{-1}. These values differ by a factor of 11. The highest uptake of CO_2 that occurred around noon was in July (2.36 g CO_2 m^{-2} h^{-1}). Also in this month the highest night flux was observed, on average a release of 0.629 g CO_2 m^{-2} h^{-1}.

The diurnal pattern of CO_2 disappeared in October. From November onwards, only positive fluxes were measured. The diurnal pattern of CH_4 continued for 1 month longer and almost vanished in November.

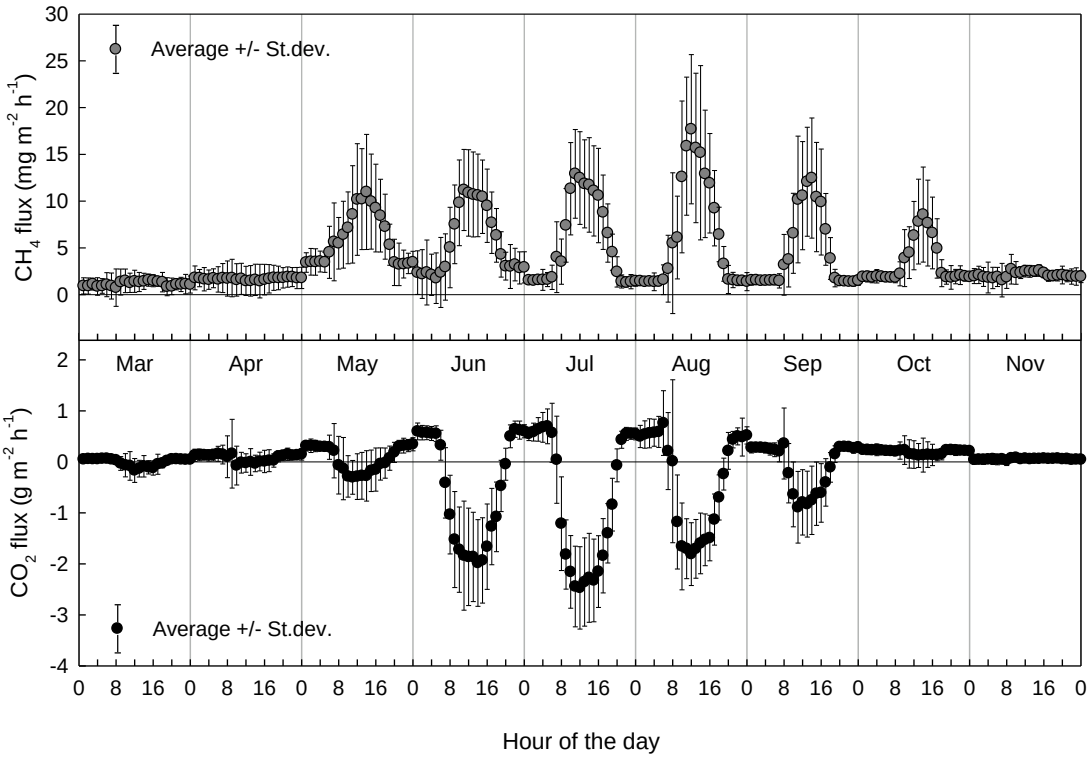

Fig. 2.3 Diurnal cycles of CH_4 (above) and CO_2 (below) from March to November 2013. Each point represents the flux averaged over a specific hour of the day averaged over 1 month. Error bars denote standard deviations.

2.3.3 Factors affecting the fluxes during growing season

Fig. 2.4 shows the results of the partial correlation analysis of the half-hourly data for the growing period (May–October). CH_4 flux shows the highest correlation with global radiation, followed by relative humidity and air temperature. The biserial correlation between CH_4 fluxes and global radiation changes very little, no matter which other factor is partialed out. This suggests that

global radiation is the most important factor influencing CH_4 fluxes. The high biserial correlation of CH_4 flux with relative humidity and air temperature decreases considerably when global radiation is partialed out. This means that the correlations of relative humidity and air temperature with the CH_4 flux are based, to a large extent, on their correlation with global radiation. It is notable that the correlation of the CH_4 flux with soil temperature is small. The correlation even becomes negative when air temperature is partialed out. During the winter period, results differ: CH_4 flux correlates most with soil temperature (r = 0.371), followed by water table height (r = 0.222; data not shown).

The correlation table for CO_2 fluxes shows the same pattern but is the inverse of CH_4, except that the correlations with air and soil temperature are higher than those of CH_4.

The impact of environmental factors on the daily fluxes of CH_4 and CO_2 fluxes was evaluated by regression analysis in the framework of the ARIMA approach. An ARIMA (0,1,1) model was found

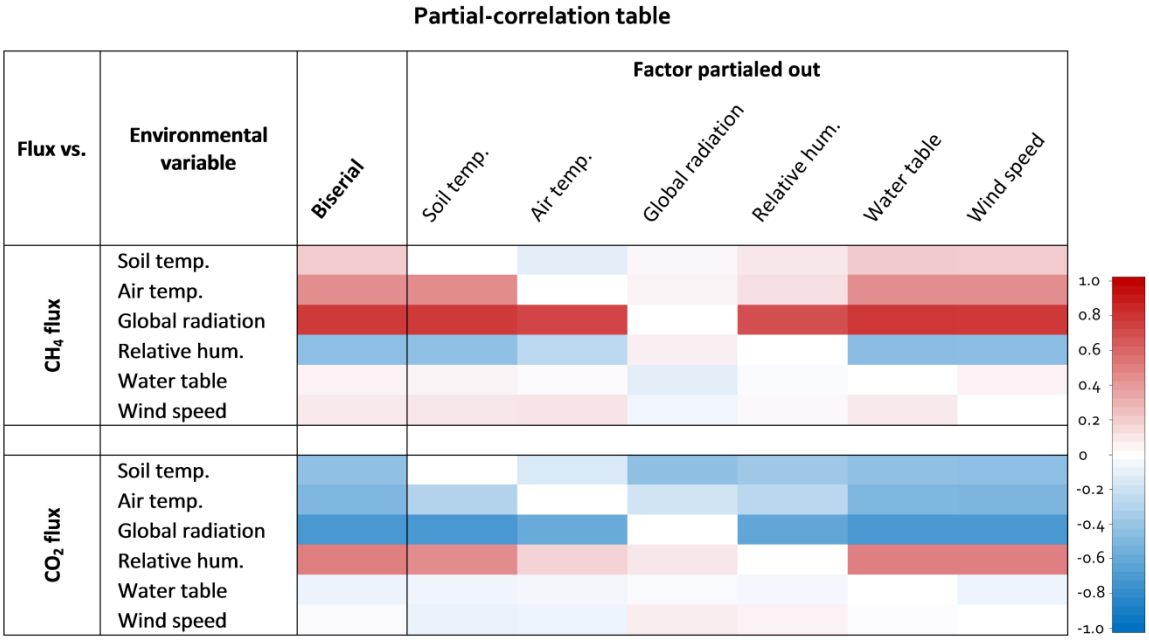

Fig. 2.4 Biserial and partial correlations between CH_4 flux (above) or CO_2 flux (below) and environmental variables within the growing season (May–October). Each variable (soil temperature, air temperature, global radiation, relative humidity, water table height and wind speed) is partialed out and the corresponding correlations with the other variables are shown in the same column. The darker the cells the higher the correlation coefficient, with the red colors for positive correlations and blue colors for negative correlations.

to be suited to model the flux time series of both CH_4 and CO_2 (Table 1). Global radiation turned out to be the only regressor with a statistically significant impact ($P < 0.05$) on the CH_4 fluxes, and global radiation and soil temperature on the CO_2 fluxes. A second order polynomial model describes the relation between global radiation and CH_4 flux as well as CO_2 flux best. In the CO_2

model, the addition of soil temperature as a linear regression term gave the best model results. Other environmental factors, such as relative humidity and air temperature, also covary with the fluxes, but their possible impact on the fluxes cannot be determined because it is screened due to their correlation with global radiation and soil temperature. After differencing the data, the resulting models for CH_4 and CO_2, are given by Eqs. (2.2) and (2.3):

$$\Delta CH_4 flux_t = \beta_1 * \Delta Rg_t + \beta_2 * \Delta Rg_t^2 + e_t - \theta * e_{t-1} \quad (2.2)$$

$$\Delta CO_2 flux_t = \beta_1 * \Delta Tsoil_t + \beta_2 * \Delta Rg_t + \beta_3 * \Delta Rg_t^2 + e_t - \theta * e_{t-1} \quad (2.3)$$

where Δ is the differencing operator (e.g, $\Delta CH_{4,t} = CH_{4,t} - CH_{4,t-1}$), β a regression coefficient, θ the weight of the moving average (MA) term and e_t the residual error term that is assumed to

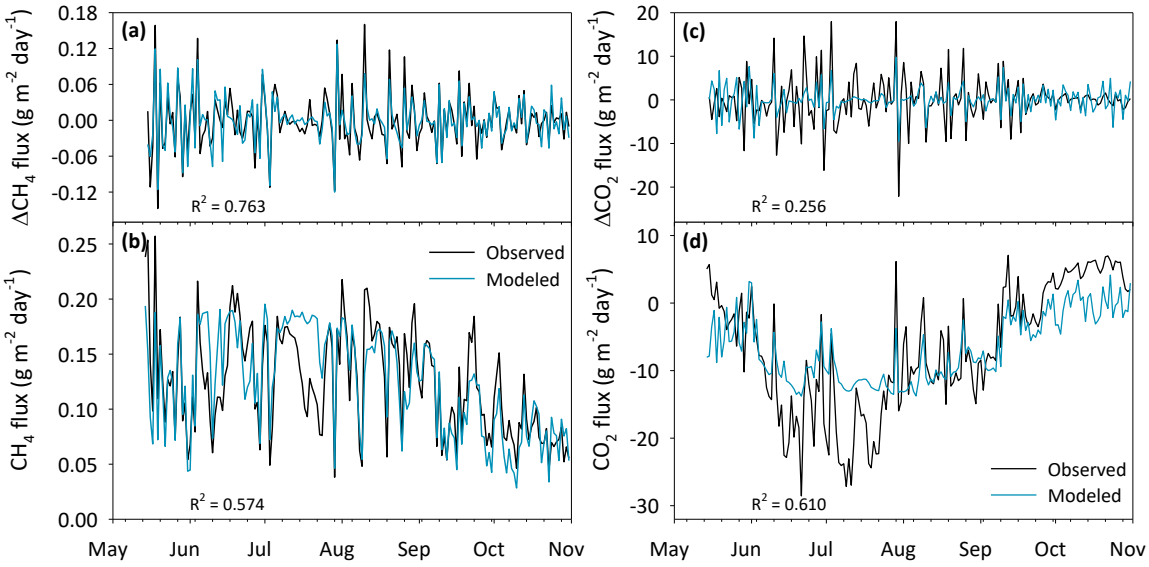

Fig. 2.5 Observed and modeled daily fluxes of (a) differenced data for CH_4, (b) original data for CH_4, (c) differenced data for CO_2 and (d) original data for CO_2. The modeled data are created with an ARIMA (0,1,1) model, with Rg as the explaining variable for CH_4, and Rg and T_{soil} for CO_2. The error terms with the autoregressive part for the modeled data are not included in these graphs or in the coefficients of determination (R^2).

be independently normally distributed (white noise). The coefficient of determination (R^2) of the CH_4 model with differenced data is 0.79. Without the error term ($e_t - \theta * e_{t-1}$), R^2 is 0.76. In the case of CO_2, the model performance is much lower (R^2 = 0.47 with error term and R^2 = 0.26 without error term). For comparison, when only the regression part of the model is run with non-differenced data (CH_4 flux = constant + $\beta * Rg_t$) the coefficient of determination became 0.57. In the case of CO_2, the respective value is 0.61. Fig. 2.5 gives an impression of the model performance over time, again without making use of the error terms for the predictions.

Table 2.1 Model parameters and statistics of the CO_2 and CH_4 ARIMA (0, 1, 1) models.

	CH_4 flux (g m^{-2} day^{-1})			CO_2 flux (g m^{-2} day^{-1})		
Model variable	Coefficient (β, θ)	t	P value	Coefficient (β, θ)	t	P value
Rg (W m^{-2})	$7.15.10^{-4}$	8.83	<0.000	-0.0859	-5.42	<0.000
Rg^2 (W m^{-2})	$-6.07.10^{-7}$	-2.94	0.004	$1.36.10^{-4}$	3.41	0.001
T_{soil} (°C)				-0.950	-2.56	0.0211
MA lag 1	0.388	5.41	<0.000	0.671	11.2	<0.000

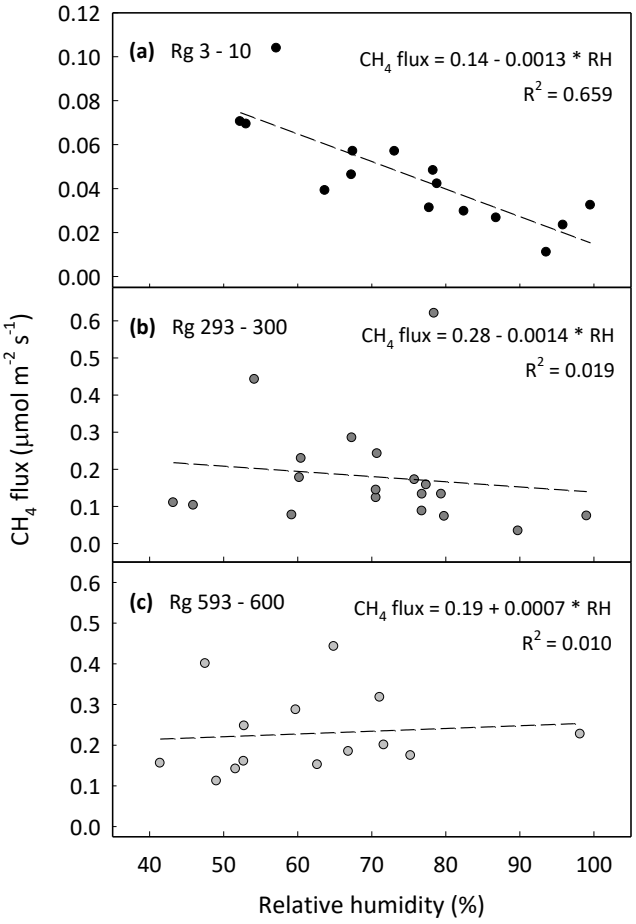

Fig. 2.6 CH_4 flux plotted against relative humidity (RH). Data are selected by global radiation (Rg) in the range (a) 3–10, (b) 293–300 and (c) 593–600 W m^{-2}. Only data with a corresponding air temperature between 10–20 °C are displayed.

The high correlation of global radiation with the CH_4 fluxes suggests an influence of the plants on the fluxes. The internal gas transport mechanism of *Phragmites* (HIC) is expected to be regulated by the stomata (influenced by radiation) and humidity differences between the atmosphere and plant culm. Because relative humidity highly correlates with global radiation, we selected small intervals of global radiation within a temperature range between 10–20 °C and evaluated the correlation between relative humidity and CH_4 fluxes within these intervals (see Fig. 2.6). Only with low radiation (3–10 W m^{-2}) is there a clear negative correlation. With higher radiation intensities (293–300 and 593–600 W m^{-2}) the correlation disappears.

2.3.4 Carbon and greenhouse gas balance

Fig. 2.7a shows the monthly cumulative fluxes of R_{eco}, GEP and CH_4. The highest fluxes for R_{eco} and GEP were measured in July and for CH_4 in August (3.5 g C m^{-2}). The contribution of CH_4, however, to the overall carbon flux is minor. From June to September, the contribution of GEP was higher than that of R_{eco} plus CH_4, resulting in a net carbon uptake during these months. This uptake more than compensates the net release of carbon in the other months. The net yearly CO_2 uptake was 894 g m^{-2} yr^{-1} and the CH_4 emission was 30 g m^{-2} yr^{-1} (see Table 2.2). This leads to a net annual uptake of carbon of 221 g C m^{-2} by the reed ecosystem, corresponding to 26% of the GEP. CH_4 plays a minor role in the carbon balance, but with a global warming potential

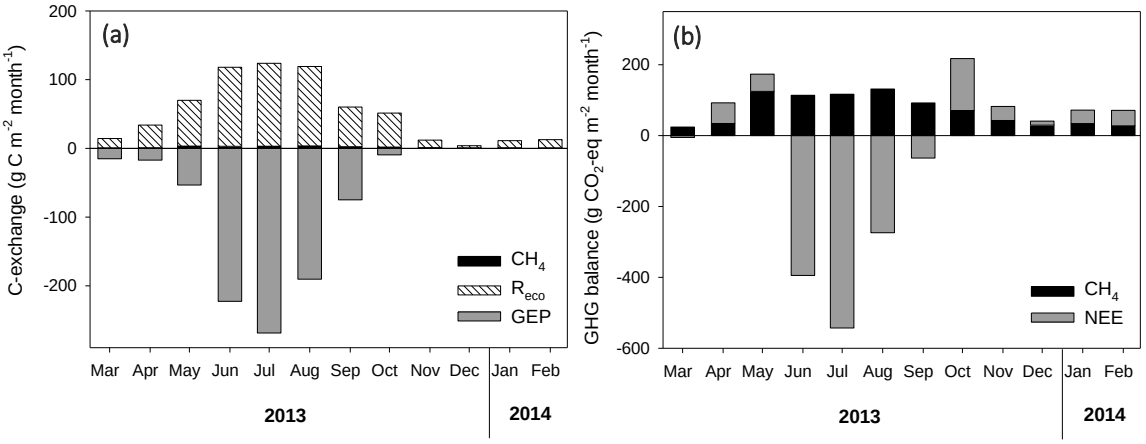

Fig. 2.7 (a) Monthly accumulated carbon fluxes from CH_4 and CO_2 divided between ecosystem respiration (R_{eco}) and gross ecosystem production (GEP). (b) Carbon fluxes in CO_2 equivalence from CO_2 (net ecosystem exchange, NEE) and CH_4, where CH_4 fluxes are multiplied by a global warming potential (GWP_{100}) of factor 28 (IPCC, 2013).

Table 2.2 Annual integrated flux, carbon balance and greenhouse gas (GHG) balance for CH_4, CO_2 and the sum of both gases for carbon and GHG balance.

	Integrated flux (g m^{-2})	Carbon balance (g C m^{-2})	GHG balance (g CO_2-eq m^{-2})
CH_4	30	23	842
CO_2	-894	-244	-894
Sum		-221	-52

(GWP) of 28 (GWP_{100}, IPCC 2013), it heavily affects the greenhouse gas balance (see Fig. 2.7b). With an uptake of 52 g CO_2 eq. m^{-2} yr^{-1}, the ecosystem is a minor greenhouse gas sink (see Table 2.2).

2.4 DISCUSSION

2.4.1 CH_4 FLUXES AND PLANT-MEDIATED GAS TRANSPORT

In the period that the above-ground plant parts were alive and green, we observed a distinct diurnal pattern in the CH_4 fluxes. The highest emission was observed around noon and the lowest during the night. Similar diurnal CH_4 flux patterns from *Phragmites*-dominated wetlands were reported by Kim et al. (1998b), who used the EC method and by van der Nat et al. (1998) and Grünfeld and Brix (1999), who performed studies with closed chambers. The observed pattern can be explained by the gas transport mechanism within the culm of the *Phragmites* plants. This mechanism is described by Armstrong and Armstrong (1990, 1991) and Armstrong et al. (1992, 1996a, b) as HIC. According to these publications, a convective flow is generated due to an elevated air pressure in the plant stem caused by a humidity gradient (regulated by the stomata) between the inner part of the leaf sheaths and the atmosphere. The higher pressure creates an air flow through the entire stem and rhizomes that is vented via old (broken) stems. This process starts after sunrise, is at its optimum in the early afternoon and decreases until sunset (Brix et al., 2001). During the night, when stomata are closed, gas transport in the stems solely takes place via diffusion. Arkebauer et al. (2001) measured air pressure in stems of *Phragmites* in the field and observed the same diurnal pattern as we found in the CH_4 flux data. Brix et al. (1992a) found the same pattern with four different wetland plants (including *Phragmites*). They both showed that stem pressure (and convective flow in Brix et al., 1992b) correlates with radiation, air temperature and relative humidity. These correlations with HIC were also found in lab experiments (Armstrong and Armstrong, 1991). We found only a strong correlation of CH_4 fluxes with global radiation during the growing season. The correlations we found with air temperature and relative humidity can also be explained by the dependency of these variables on global radiation. It is unexpected that the correlation with relative humidity is not prominent, since this is the driving factor behind HIC. Armstrong and Armstrong (1991) found that convective flow and relative humidity were negatively correlated with a convective flow close to 0 and a relative humidity of 100 %. This lab experiment, however, was carried out with a very low, constant light intensity (4.4 W m^{-2}). Sunlight intensity can be more than 200 times higher. When we selected our measured data within the same light intensity range (Rg 3–10 W m^{-2}), we found exactly the same negative correlation between CH_4 fluxes and relative humidity as Armstrong and Armstrong (1991). With higher light intensities, however, the correlation vanished. In that same study and in another study (Armstrong and Armstrong, 1990) a correlation was found between photosynthetically active radiation (PAR) and air flow within the plant stem. Radiation can create a temperature difference between the stem and air, this increases the pressure inside the stem

compared to the air pressure, which can also create a convective flow. This phenomenon is called thermal transpiration, but in *Phragmites* the contribution is believed to be small (Armstrong and Armstrong, 1991; Armstrong et al., 1996a). It also appears that convective flow increases much more with PAR than with infrared radiation (Armstrong and Armstrong, 1990), which speaks against the thermal transpiration hypothesis. The strong correlation between global radiation and CH_4 flux that we observed and the fact that the dominant role of radiation was confirmed in the ARIMA analysis suggests that a mechanism related to stomatal control or photosynthesis might play a role in the creation of a convective flow. But the question still remains how? Based on our data we cannot give an answer to this question.

We found the highest midday–night difference was in the month of August when the reed was fully grown. On average, midday emissions during this month were 11 times higher than at night. This is more than 2 times higher than the highest difference Kim et al. (1998b) found in a *Phragmites*-dominated marsh in Nebraska. In a lab experiment by Grünfeld and Brix (1999), midday and night fluxes differed by a factor 2.5, which is also much lower than in our study. The reason for this deviation might be the density of the *Phragmites* plants for which convective flow is expected to be directly proportional. At our site, the density of living green *Phragmites* plants is almost twice as high (68 m^{-2}) as in the prairie marsh in Nebraska (Kim et al., 1998b).

The question remains whether the overall CH_4 flux increases or decreases due to the presence of living, green reed. In our data, we found a very clear increase in the daily CH_4 flux after the beginning of reed growth. Soil temperature also increased in the month of May, but not in proportion to the CH_4 flux. An increase of the CH_4 flux due to the presence of living reed would be in contradiction to an experiment performed by Grünfeld and Brix (1999). They found a decrease in the CH_4 emissions of 34% with the addition of *Phragmites* to a submerged organic soil. Their explanation is that methanogenesis is reduced and CH_4 oxidation increased because of the transport of oxygen by *Phragmites* into the rhizosphere. In a soil without reed, the gas transport would be dominated by ebullition. Transport by ebullition is faster than internal plant transport, so that less of the produced methane is oxidized. Hendriks et al. (2010) found the opposite in a field study with water table differences and vascular wetland plants. A high water table and vascular plants showed higher methane emission than the same soil and water table without vascular plants. Kankaala et al. (2004) found a higher contribution of ebullition to the CH_4 flux in a less dense *Phragmites* shore zone (24 shoots m^{-2}) than in a dense area (78 shoots m^{-2}). The less dense *Phragmites* zone showed 3-fold higher CH_4 emissions than the denser area. Koch et al. (2014) also found a negative correlation of methane fluxes with *Phragmites* abundance. Given this negative correlation, the high density of 68 shoots m^{-2} at our site would suggest that total CH_4 flux would be lower compared to wetlands with lower densities. Our observed yearly

CH_4 flux of 30 g m^{-2} yr^{-1} is in the same range as Kankaala et al. (2004), who found similar dense reed vegetation (20–50 g m^{-2} yr^{-1}) and indeed almost 3 times lower than the flux measured by Kim et al. (1998b) in a reed density of only 35 shoots m^{-2}. So even though our site has a relative low net CH_4 flux, it is likely that plant-mediated gas transport during the growing season could lead to higher CH_4 emissions compared to winter, if in both seasons the ebullition is reduced due to the plant density.

2.4.2 EFFECT OF OTHER ENVIRONMENTAL FACTORS ON CH_4

Another influence of the plants on the CH_4 fluxes could be the release of root exudates, which is closely linked to photosynthesis. Root exudates lead to an increase in substrate availability in the form of easily decomposable organic compounds, which can be used by methanogens to produce CH_4 (Aulakh et al., 2001; Christensen et al., 2003). There are studies that found positive correlations between radiation or net ecosystem production and CH_4 flux (Whiting and Chanton, 1993; Joabsson and Christensen, 2001), although there are also studies that found the opposite (Mikkelä et al., 1995; Ström et al., 2005). Ström et al. explain the negative correlation of the CH_4 oxidation rate, depending on the oxygen transport capacity of the plants. In general, we expect that there should be an effect of photosynthesis on the CH_4 flux because plant photosynthates are an important carbon source for methanogens (Philippot et al., 2009). It is, nevertheless, hard to say how much the diurnal pattern is influenced by this. In our data we see that on average the maximum CH_4 flux appears almost at the same time as the maximum CO_2 uptake. The question, however, is if the response time between photosynthesis and excretion of root exudates to the production of CH_4 could be that fast. Most studies that relate root exudation to CH_4 flux or production did not measure in hourly resolution. Nevertheless, Aulakh et al. (2001) found a CH_4 production peak 1 day after adding root exudates to pre-incubated clay soils, whereas Ström et al. (2005) found emission peaks for CH_4 and CO_2 more than 2 days after adding labeled acetate to soil with wetland plants in monoliths. Another reason why we assume that the diurnal pattern is mainly caused by the internal pressurized convective flow of the plants builds on the observation that there is still a diurnal pattern for CH_4 flux visible in October: photosynthesis has come to an end, but the plants are still (partly) alive.

During winter, the daily pattern in the CH_4 fluxes was no longer visible. Dead culms of reed are able to transport O_2 into the soil and CH_4 and CO_2 from the soil to the atmosphere, but only by diffusion (Brix, 1989). During the winter months, correlations of gas fluxes with environmental variables were low. Nevertheless, the highest correlation was with soil temperature. This suggests that soil temperature played the dominant role during this period. Soil temperature influences microbial activity (Moore, 1994; Le Mer and Roger, 2001). It also influences respiration, which

influences the availability of substrate needed for methanogenesis (CO_2, acetate; Christensen et al., 2003). Therefore, an increase in temperature leads to higher emissions. Water table height is known to have a large impact on CH_4 fluxes (Moore and Knowles, 1989; Aerts and Ludwig, 1997; Grünfeld and Brix, 1999; Updegraff et al., 2001), but only for non-flooded peatlands. In our case, the impact was small because the water table was always above surface level (5–40 cm) so that the soil remained anoxic.

2.4.3 CO_2 FLUX PATTERNS

Also CO_2 fluxes exhibited clear diurnal and seasonal patterns. The fluxes were mainly influenced by the presence of green plants (high negative correlation with global radiation) and temperature changes. A similar diurnal and seasonal variation was observed in a *Phragmites* wetland in northeast China based on EC measurements (Zhou et al., 2009). They also observed the highest CO_2 uptake in July with -13.6 g CO_2 m^{-2} day^{-1}, which is lower than our measured uptake of -17.5 g CO_2 m^{-2} day^{-1}, and a small release of CO_2 in winter, which is in the same range (2.6 g CO_2 m^{-2} day^{-1} vs. 2.7 kg CO_2 m^{-2} day^{-1}) as our observations. The difference in July can be explained by the much higher soil and ambient temperature in the study by Zhou et al. (2009), which resulted in higher R_{eco} relative to the increase in assimilation.

The Q_{10} values based on soil temperature in the study by Zhou et al. (2009) are within the same range (4.1 in May to 1.8 in September–October) as what we found (3.93 in May–June to 1.53 September–October). This number is still higher than the Q_{10} value found by Mahecha et al. (2010) based on a global collection of FLUXNET data. A possible reason might be that we used soil temperature instead of air temperature. Soil temperature gave a much better fit in the regression and soil respiration is also expected to have a high contribution due to the high carbon content in the soil. But plant respiration also contributes a certain fraction and is more dependent on air temperature. Due to the almost permanent water logging at the study site, the difference between the ranges of air night temperatures and soil night temperatures was particularly large.

2.4.4 ECOSYSTEM AS A CARBON AND GREENHOUSE GAS SINK

The yearly CO_2 uptake was 894 g m^{-2} yr^{-1}, and the CH_4 emission 30 g m^{-2} yr^{-1}. The CO_2 uptake is almost 4 times higher than in a *Phragmites* wetland in China (Zhou et al., 2009). The difference could be explained by the lower temperature at our site, so that the respiration rate is lower. Our CH_4 flux is in the same range as at sites with similar *Phragmites* densities (see above). More generally, northern fens show a wide variation in CH_4 fluxes, from close to 0 to 300 g CH_4 m^{-2} yr^{-1}, depending on temperature, water table and vegetation cover, among others (Lai, 2009; Kayranli et al., 2010). Our site is at the lower range of that spectrum. Summing up CO_2 and CH_4 fluxes of our ecosystem leads to the net annual carbon uptake of 220 g C m^{-2}, which is 26% of the GEP. It

should be noted that the calculated respiration rate during daytime might be underestimated due to the plant-mediated gas transport. Brix et al. (1996) measured that around noon, 5 times more CO_2 was transported from the soil to the atmosphere by *Phragmites* plants compared to the early evening. Because daytime respiration is only estimated from its nighttime relationship with soil temperature, respiration could be underestimated, and therefore the GEP as well. This would mean that the percentage of the GEP stored in the system would be lower than is given above. It is however, hard to say how much lower, since we cannot independently assess the respiration rate during daytime.

The carbon uptake at our site is much higher than the 65 g C m^{-2} (5% of the GEP) measured in the *Phragmites*-dominated wetland in northeast China (Zhou et al., 2009; CH_4 is not considered). But it is only half as high as the uptake estimated for a *Phragmites*-dominated wetland in Denmark (550 g C m^{-2} yr^{-1}, 47% of GEP; Brix et al., 2001). The temperature during the growing season was lower than in the Chinese wetland, on average even 10 °C lower in July. Zhou et al. calculated a much higher R_{eco}, which may have caused the difference. The wetland described by Brix et al. (2001) has a similar R_{eco} to ours, but a 30% higher GEP, which explains the diverging findings. Our measured uptake of 65 g C m^{-2} yr^{-1} fits in the wide range of measured carbon exchange in northern peatlands: from an uptake of 220 g C m^{-2} yr^{-1} to a release of 310 g C m^{-2} yr^{-1} (Strack, 2008). In the long term, the uptake of northern peatlands is on average between 20–50 g C m^{-2} yr^{-1} (Strack, 2008). A longer measurement period may be needed however, to ensure that C uptake at our site falls indeed into this range.

2.5 CONCLUSIONS

Our CH_4 fluxes show distinct diurnal cycles, but only in the period when living green plants were present. This strongly suggests that plant-mediated gas transport in *Phragmites* plays an important role regarding the emission of CH_4 from a natural fen site in Federseemoor, southwest Germany. The convective flow within the plant is probably not solely driven by the humidity gradient between the interior of the plant and the ambient air (HIC theory). From our data it is more likely that global radiation plays a more significant role in creating a higher pressure inside the plant.

Our research site is a sink for both carbon (-221 g C m^{-2} yr^{-1}) and greenhouse gases (-52 g CO_2 eq. m^{-2} yr^{-1}) in the year studied. This is probably due to the high productivity of *Phragmites* plants, the high water table and the relatively cold climate, so that respiration rates are relatively low. Thereby, the low CH_4 emission compared to other *Phragmites* wetlands can be explained by the high plant density in our system, which could reduce ebullition.

In general, wetland plants that can enhance gas transport, such as *Phragmites*, are important to consider for determining the impact of these wetlands on climate change. The role of environmental factors such as global radiation and relative humidity on the convective flow within *Phragmites* should be further investigated. This would be helpful in gaining more knowledge about the contribution of plant-mediated transport to net fluxes of CH_4 and CO_2.

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Chapter 3

Contribution of plant-induced pressurized flow to CH_4 emission from a *Phragmites* fen

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ABSTRACT

The widespread wetland species *Phragmites australis* (common reed) has the ability to transport gases through its aerenchymatous stems via a pressurized (convective) flow rather than internal diffusive flow only. This results in higher oxygen (O_2) transport to the roots and rhizosphere, and simultaneously higher soil methane (CH_4) and carbon dioxide (CO_2) transport in the opposite direction to the atmosphere. As this plant-mediated transport leads to higher O_2 intrusion into the soil, it may suppress microbial CH_4 production and stimulates CH_4 oxidation, leading to lower overall CH_4 emission. At the same time, however, CH_4 is more easily transported to the atmosphere, bypassing the oxic soil and surface water layer. This raises the question how pressurized gas transport through wetland plants affects CH_4 emission compared to a situation where gas transport is dominated by diffusion and ebullition from the soil.

A field experiment was set-up in a *Phragmites*-dominated fen in southwest Germany, measuring CH_4 fluxes with transparent chambers from 1) plots with intact *Phragmites* vegetation (control), 2) plots where *Phragmites* culms clipped (CR) to exclude the pressurized flow but include diffusive flow from the clipped stems, and 3) plots where culms were clipped and sealed (CSR) to exclude any transport through the plants. In addition, ebullition from the soil was determined to assess the relative contribution of all three gas transport pathways from the soil to the atmosphere (plant-mediated, soil diffusive and soil ebullition) for each treatment. As a data quality check, CH_4 fluxes from the control plots were compared to eddy covariance fluxes from the same location. Fluxes derived from both methods were similar in magnitude and diurnal patterns, meaning that the chamber method gives representative CH_4 fluxes for this *Phragmites* system. Clipping the stems resulted in a reduced diffusive and plant-mediated flux by about 60% (control: 517 mg m^{-2} day^{-1} vs 217 and 279 mg m^{-2} day^{-1} for CR and CSR). Simultaneously, ebullition from the soil strongly increased by a factor of 7 by clipping (10 versus 71 mg m^{-2} day^{-1}) to even 13 by clipping and sealing (126 mg m^{-2} day^{-1}). This increase of ebullition did, however, not compensate for the exclusion of gas transport via plant-related pressurized air flow. Total CH_4 emission (chamber flux + ebullition) from the control was 2.3 and 1.3 times higher than from CR and CSR respectively, demonstrating the significant role of pressurized gas transport in *Phragmites* stands. The results also show that excluding pressurized flow leads to increased CH_4 oxidation and/or lower CH_4 production.

We conclude that stands of plants with pressurized gas transport mechanism are important contributors to the overall CH_4 emission from wetlands.

3.1 INTRODUCTION

Methane (CH_4) produced in soils is to a great extent oxidized to CO_2 before it reaches the atmosphere (Le Mer and Roger, 2001; Lai, 2009). The proportion of oxidation depends on water table height (Le Mer and Roger, 2001; Brix et al., 2001; Lai, 2009) and the presence or absence of vascular wetland plants (Grünfeld and Brix, 1999; Hendriks et al., 2010). Both factors influence the concentration of oxygen (O_2) in the soil (Armstrong and Armstrong, 1990; Brix et al., 1992) and the pathways by which CH_4 is transported from the soil to the atmosphere (Le Mer and Roger, 2001; Hendriks et al., 2010). There are three gas transport pathways: diffusion and ebullition from the soil, and plant-mediated transport via aerenchyma of roots and stems of vascular plants.

Diffusion is a relatively slow process, whereby a large part of the produced CH_4 is oxidized when crossing the oxic upper layer of the water column or soil (Lai, 2009). Ebullition occurs when a submerged soil is supersaturated with gas and bubbles are formed. These bubbles can rapidly pass through the water-saturated soil and water column above. Because this transport is fast, only a small part of the CH_4 can be oxidized. In general, ebullition is affected by temperature, air pressure and water table height (influencing the pressure in the water column), however, it shows a high spatial and temporal variation and is hard to predict (Fechner-Levy and Hemond, 1996; Kellner et al., 2006; Lai, 2009; Hendriks et al., 2010). The contribution of ebullition to the overall CH_4 flux ranges from a few percent (Green and Baird, 2013) to more than 50% (Christensen et al., 2003).

CH_4 transport mediated by wetland plants occurs through aerenchyma tissue, which has the physiological function to transport O_2 into the roots. Often, more O_2 is transported to the roots than is consumed, leading to O_2 leakage into the rhizosphere (Colmer, 2003). Besides O_2 transport into the soil, other gases (e.g. CO_2 and CH_4) can simultaneously be transported from the soil to the atmosphere (Chanton et al., 2002; Lambers et al., 2008). This gas transport via aerenchyma tissue can occur via a diffusion gradient or by a pressure gradient that is built up by the plants (Armstrong and Armstrong, 1991; Brix et al., 1992). Plants that transport gases via diffusion are, among others, *Carex rostrate*, *Oryza sativa*, *Scirpus Lacustris* and *Peltandra virginica* (van der Nat et al., 1998; Chanton et al., 2002) whereas gas transport via convective through-flow is found in *Typha latifolia*, *Typha angustifolia*, *Nymphaea odorata*, *Nuphar luteum*, *Nelumbo nucifera*, *Nymphoides pelata* and *Phragmites australis* (Brix et al., 1992; Chanton et al., 2002). Gas transport in *Phragmites australis* (common reed) is highly effective. It builds up a humidity-induced pressure gradient within the leaf sheaths (the part of the leaf that encircles the stem) that leads to an airflow from the leaf sheaths towards the rhizomes and is vented via old and broken stems (Armstrong and Armstrong, 1990; Armstrong and Armstrong, 1991; Armstrong et

al., 1996; Afreen et al., 2007). This transport mechanism is more than 5 times faster than diffusion (Brix et al., 2001) and is regulated by the pores (stomata) in the leaf sheaths. These stomata do not transport gas caused by pressure differences, but allow gas transport by diffusion. Due to higher humidity in the internal culm of *Phragmites*, O_2 and N_2 concentrations inside the plant are diluted. Therefore, O_2 and N_2 are transported along the concentration gradient from the atmosphere into the sheaths, increasing the internal pressure (see Fig. 1.5, chapter 1). Since this process depends on stomatal conductance, humidity induced convective flow starts after sunrise when the stomata open, reaches an optimum around noon when photosynthetic rates are highest and then decreases till sunset (Brix et al., 2001). Therefore, this diurnal cycle is also observed in CH_4 fluxes from *Phragmites* wetlands during the growing season (Kim et al., 1998; van der Nat et al., 1998; Grünfeld and Brix, 1999; van den Berg et al., 2016). On the one hand, *Phragmites* transports O_2 into the soil, which leads to higher oxidation rates of CH_4 and can also be expected to reduce methanogenesis. On the other hand, transport of CH_4 from the soil to the atmosphere through the plant is facilitated, bypassing the oxic soil and water layer. Grünfeld and Brix (1999) showed a 34% decrease in CH_4 emission after addition of *Phragmites* to a submerged organic soil. In contrast, Hendriks et al. (2010) found that vascular plant presence (among others *Phragmites* and *Thypha latifolia*) lead to higher methane emissions, but is depending on the water table height.

Since the findings in literature are not unambiguous, the following questions remain: 1) how important is plant-mediated gas transport in *Phragmites* compared to the other CH_4 transport mechanisms (diffusion and ebullition from the soil); 2) how does *Phragmites* influence diffusive and ebullition fluxes; and 3) does the presence of *Phragmites* stands lead to an overall increase or decrease of CH_4 emission? To study this, a field experiment was set-up in a large reed area of a minerotrophic peatland. To quantify the importance of plant-mediated CH_4 transport at a community level, we compared fluxes measured with chambers from control *Phragmites* plots with plots where *Phragmites* culms were clipped to exclude pressured gas transport through the plant. To exclude any gas transport through plants, we also measured CH_4 fluxes from plots where *Phragmites* culms were clipped and sealed. Ebullition from the soil was determined as well, to assess the relative contribution of all gas transport pathways of CH_4 from a reed fen.

In addition to the experiment, we were interested to see if the chamber fluxes from the control plots were representative for the system. Therefore, we made a comparison between CH_4 fluxes measured with the chamber method and with the eddy-covariance method.

3.2 MATERIAL & METHODS

3.2.1 STUDY SITE

The study was conducted in the Federseemoor (48.092°N, 9.636°E), a peatland of 30 km^2 located in the region Upper Swabia in southwest Germany. This peatland has developed via natural terrestrialization from a proglacial lake after the last ice age. As a result, the surface area of the lake declined from 30 km^2 to 12 km^2. Between 1787 and 1808, the lake was further reduced to a size of 1.4 km^2 by drainage activities. The newly gained land of 11 km^2 was used as pasture but turned out to be unprofitable due to the recurring high water table. Nowadays it is a nature conservation area, mainly consisting of fen (see van den Berg et al., 2016 for a vegetation map). The lake Federsee is completely surrounded by reed vegetation (*Phragmites australis* (Cav.) Trin. ex Steud), with a total area of 2.2 km^2 and a density of around 70 living shoots per m^2. During the measurement period (7-10 June) *Phragmites* plants were 1.2 m high. This is half their maximum height, which will be reached at the end of July. The high density of *Phragmites* and lack of other species in the reed belt result from high nutrient concentrations due to wastewater input to the lake since 1951. After 1982, the input of untreated sewage water was stopped, which reduced the nutrient concentrations. However, only since 2006 the water quality has improved significantly and after 2008 the lake water became clear again. The field experiment was installed in the middle of the reed area at around 50 m distance from an eddy covariance (EC) tower, which is running since March 2013 (van den Berg et al., 2016).

3.2.2 FIELD EXPERIMENT

Nine plots of 2 m x 2 m were prepared, for 3 treatments with 3 replicates: 1) clipped reed (CR), to exclude the pressurized flow in the plants; 2) clipped and sealed reed (CSR), to exclude any exchange via plant stems; and 3) control where reed was not manipulated. In the CR and CSR treatments, reed was clipped to about 10 cm above the water table. In the CSR treatment the clipped reed culm was sealed with acrylic kit. Since rhizomes connect plants over longer distances, plots were isolated by clipping roots from the reed plants around each plot to a depth of 50 cm, to avoid gas exchange with the surrounding area. The period between preparation of the plots and measurements was minimized (1 to 2 days) to reduce possible side effects, such as root die-off. However, one day before the 1st measurement the water table rose about 20 cm, flooding the prepared clipped and sealed stems of one plot. Nevertheless, since no gas exchange is expected from the sealed stems, this plot was still included in the experiment. CH_4 and CO_2 diffusive fluxes from the soil and plant-mediated fluxes were measured with transparent flow through chambers. Pore water was extracted to analyze the effect of the reduced/excluded gas exchange by the plants on soil chemistry. In each plot ebullition was measured as well.

3.2.3 DIFFUSIVE AND PLANT MEDIATED CH_4 FLUX

On 7, 9 and 10 June 2016 between 06:00 and 18:00, gas fluxes of each treatment were alternately measured. Per day, only one of the triplicates per treatment was measured. Plots were covered by transparent chambers with a diameter of 50 cm. One chamber was 2 meters high and was on the control plots. Two chambers were 1 meter high and used on CR and CSR plots. The 1 meter chambers were equipped with a small fan of 8 cm x 8 cm that had a flow capacity of 850 l/min.; two fans were installed in the 2-meter chamber. Each day one replicate of every treatment was measured, to be able to capture the diurnal cycle for each plot and to minimize disturbance by translocating the chambers. The chambers were connected with 8 m tubing to a Multiport Inlet Unit attached to a fast greenhouse gas analyzer (GGA) with cavity ringdown spectroscopy (GGA-24EP, Los Gatos Research, USA) measuring the concentration of CH_4 and CO_2 every second. Every 5 minutes the Multiport switched between the three chambers, allowing air from each chamber to be alternately pumped through the GGA with a pumping rate of 300 ml min^{-1}. The withdrawn air from the chamber was replaced with ambient air through an opening in the chamber. After 1-2 hours of continuous measurements, the chambers were ventilated by lifting the chambers to fully replace inside air with ambient air. Since it takes a long time before the chamber CH_4 gets to equilibrium with the water column, 1 to 2 hours of increasing CH_4 concentration in the chamber will have little effect on the measurement accuracy of the CH_4 flux (in contrary to the CO_2 flux) (Bastviken et al., 2010). Nevertheless, data analysis revealed that only the measurements made in the 1st 30 minutes after ventilating were useful, since later measurements appeared to be too much influenced by ebullition in the treated plots. Probably ebullition was reduced by ventilating the chambers (due to the pressure of putting the chambers back on the soil). For the control, no pattern related to time after ventilating was observed. The concentration for every measurement point was corrected for the change in concentration caused by the inflow of ambient air (assuming it has the same volume of inflow as outflow) and by the difference between chamber CO_2 and CH_4 and ambient CO_2 and CH_4 concentrations. The latter were measured by the EC station. The slope of the corrected chamber concentrations over a 4 minute period was used to calculate the flux and was checked for non-linear fluctuations due to e.g. ebullition by verifying the coefficient of determination ($R^2 > 0.7$) of the regression. All regression lines were checked visually as well, to filter out data with a non-linear increase in concentration. Also fluxes corresponding to an average chamber concentration of > 100 ppm CH_4 were discarded, because of the GGA's detection limit.

3.2.4 EBULLITION

In each plot ebullition was measured by catching bubbles from a fixed surface with an ebullition trap, composed of a 0.2 m diameter funnel, to which a glass bottle of 300 ml was attached. The ebullition trap was installed under the water table on 8 June and carefully anchored between reed stems (no open endings of stems were below the trap) on the soil surface around 0.55 m below the water surface. Bubbles were captured in the glass bottle for 18 days, after which the bottles were removed and gas samples were taken in the field. The total volume of ebullition gas was determined in the lab. The concentration of CH_4, CO_2 and N_2O were measured by gas chromatography (7890B GC, Agilent Technologies, USA).

3.2.5 ENVIRONMENTAL VARIABLES

In each chamber, temperature and radiation were measured with a temperature/light sensor (HOBO Pendant data logger, Onset Computer Corporation, USA) logging at an interval of 30 seconds. Every minute soil temperature was measured in each plot in the upper 0 to 0.05 m with a Soil Water Content Reflectometer (CS655, Campbell Scientific Inc., USA) around 0.56 m below the water table. Air temperature, air relative humidity (HMP155, Vaisala Inc., Finland) and incoming and outgoing shortwave and longwave radiation (CNR4, Kipp & Zonen Inc., The Netherlands) were measured at a height of 6 m close to or at the EC station. Groundwater table was continuously measured with a water level pressure sensor (Mini-Diver datalogger, Eijkelkamp Agrisearch Equipment Inc., The Netherlands) at 30 min. intervals.

3.2.6 PORE WATER SAMPLING AND ANALYSIS

At 2 locations in each plot, pore water was extracted anaerobically with ceramic cups (Eijkelkamp Agrisearch Equipment Inc., The Netherlands). Pore water from 0-10, 20, 30 and 50 cm depth was collected by vacuum suction in syringes and transported to the lab. In the lab, pore water was diluted with a ratio of 1:3. Dissolved organic carbon (DOC) concentration was measured with a Dimatoc 100 DOC/TN-analyzer (Dimatec, Germany). A second pore water sample was taken in vacuumed 13 ml exetainers with 3 g of NaCl. The concentration of CH_4 in the headspace of these exetainers, representing the CH_4 concentration in pore water, was determined on a HP gas chromatograph (Hewlett Packard, USA). A third pore water sample was fixed with 0.2% 2.2-bipyridin in 10% CH_3COOH buffer in the field to determine Fe(II) measuring photometrical absorption at 546 nm in the lab.

3.2.7 EDDY COVARIANCE

The EC tower was 6 meters high and consisted of a LI-7700 open path CH_4 gas analyser (LI-COR Inc., USA), a LI-7200 enclosed path CO_2/H_2O gas analyser (LI-COR Inc., USA) and a WindMaster

Pro sonic anemometer (GILL Instruments Limited Inc., UK). Molar mixing ratio/mass density of the gases and wind speed in three directions were measured at a frequency of 10 Hz.

Fluxes were calculated for an averaging interval of 15 minutes with the software EddyPro version 6.1.0. For more detailed information about the set up and calculations of the fluxes, see (van den Berg et al., 2016).

3.2.8 $\delta^{13}C$ MEASUREMENTS

CH_4 oxidation and transport lead to isotopic fractionation of $\delta^{13}C$ of CH_4 (Chanton, 2005). The difference between $\delta^{13}C$ of the CH_4 present in the soil and the CH_4 emitted to the atmosphere may therefore reveal the importance of both methane oxidation and the different emission pathways.

The natural abundance of ^{13}C in organic compounds is around 1.1 % of total carbon and the rest is ^{12}C. The ratio $^{13}C/^{12}C$ of a sample is calculated relative to the standard ratio of Pee Dee Belemnite (0.0112372):

$$\delta^{13}C(‰) = \left(\frac{(^{13}C/^{12}C)_{sample}}{(^{13}C/^{12}C)_{standard}} - 1 \right) * 1000 \quad (3.1)$$

The $\delta^{13}C$ of CH_4 tends to be much lower than the natural abundance in organic compounds, because methanotrophic prokaryotes prefer the lighter $^{12}CH_4$ to $^{13}CH_4$ thereby increasing the $\delta^{13}C$ of CH_4. Diffusion rates for $^{12}CH_4$ are higher than for $^{13}CH_4$ (Chanton et al., 2002) decreasing the $\delta^{13}C$ of the emitted CH_4 (Chanton, 2005). Although ^{13}C enrichment (compared to produced CH_4) has been found in internal spaces of plants due to CH_4 oxidation (Chanton et al., 2002), the fractionation at the plant-atmosphere surface reduces the $\delta^{13}C$ by about 12-18‰ due to the faster transport rate of $^{12}CH_4$, which makes that emitted CH_4 can have a lower fraction of $\delta^{13}C$ than the produced CH_4. Differences in $\delta^{13}C$ between sediment and overall emission are larger for plants with diffusive internal gas transport than for plants with convective gas transport (Chanton, 2005).

Since fractionation of CH_4 emitted trough ebullition in shallow waters is negligible, these gas bubbles can be used to know the isotopic composition of produced CH_4 in sediment (Chanton, 2005). We therefore compared the $\delta^{13}CH_4$ signature of ebullition gas with the signatures of CH_4 from the chambers. Gas samples from the chamber were taken when the CH_4 concentration was at least 10 times the ambient concentration, from each plot in the afternoon. The $\delta^{13}CH_4$ signature was measured with an isotope-ratio mass spectrometer Delta plus XP (Thermo Finnigan, Germany).

3.2.9 STATISTICS

Chamber fluxes were measured at different times of the day, which means that environmental variables like temperature and radiation were varying. To be able to compare the different treatments without the variation resulting from environmental conditions, an analysis of covariance (ANCOVA) was conducted with the environmental variables as covariables.

To test if the means of the ebullition measurements or pore water concentrations were different between the treatments, an analysis of variance (ANOVA) test was performed with Fishers's Least Significant Difference (LSD) post hoc test to find the specific differences between the treatments.

3.3 RESULTS

3.3.1 PORE WATER

Pore water results show small (not significant) differences in the CH_4 and Fe(II) concentration between the treatments (Fig. 3.1). Most roots are concentrated at 30 cm depth (personal observation). From this depth and lower the soil redox conditions are reduced. Fe is reduced to Fe(II), and CH_4 production is enhanced and/or CH_4 oxidation reduced, given the increase in CH_4 concentration at this depth. A significant increase is found, however, in DOC concentrations for the CSR treatment compared to the control ($p < 0.05$) at 30 cm depth.

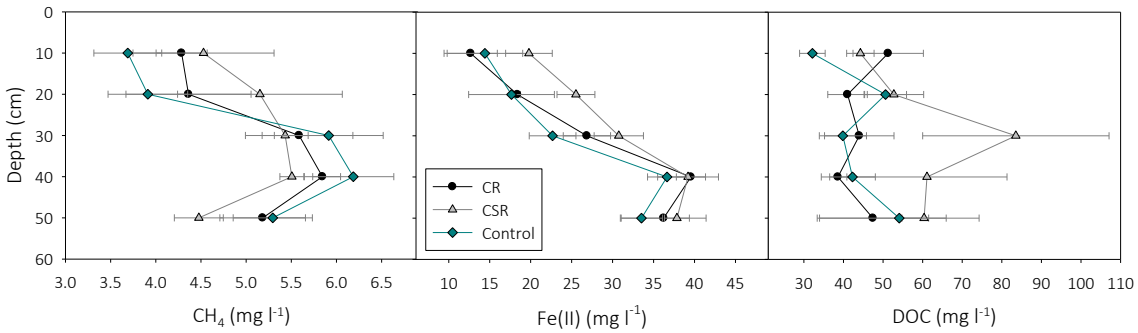

Fig. 3.1 Average dissolved CH_4 (left), Fe(II) (middle) and DOC (right) in pore water from 10 – 50 cm depth for the 2 treatments CR and CSR and the control. Error bars denote the standard error from 6 measurements.

3.3.2 COMPARISON EDDY COVARIANCE VS CHAMBER FLUXES

The CH_4 fluxes measured by the EC and the chamber method show a similar data range and show the same diurnal pattern (Fig. 3.2). The later increase in CH_4 flux on 9 June compared to the other days is most probably due to the low radiation by cloud cover and rain in the morning. From 9 June, there are no EC data available between 7:00 and 11:00 due to a rain event, which disturbed the functioning of the open-path CH_4 sensor. Chamber fluxes data that did not match the EC flux

pattern well appeared to originate from the first measurement after ventilating the chamber (see Fig. 3.2). Therefore, all first measurements after ventilating were discarded in further analyses.

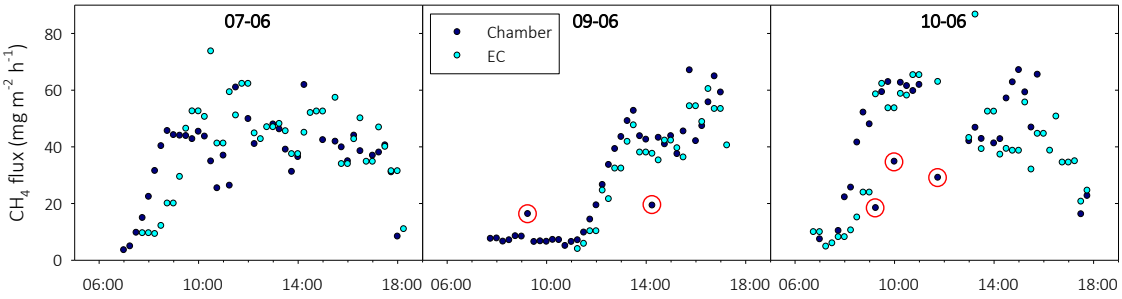

Fig. 3.2 Fluxes measured with chambers on three control plots (i.e. plots with unmodified reed stands) and with the eddy covariance method over 3 different days. The red circles point out chamber data that deviate from EC data pattern and correspond with the 1st measurement after ventilating.

3.3.3 DIFFUSIVE AND PLANT-MEDIATED FLUXES

All treatments show a diurnal cycle that correlates well with the inside air temperature of the chamber. However, the stems of the CSR plot measured on 7 June were flooded. This clearly affected the CH_4 flux and the relation with chamber air temperature (Fig. 3.3), compared to the other measurements in the CSR treatment. Flooding of the sealed stems resulted in a further decrease of the gas flux. Due to the different conditions, this plot was excluded from further data analysis. The ANCOVA analysis gives a significant result for the interaction chamber temperature * treatment ($p < 0.05$, $F = 84.2$). This interaction is used in the model, with the results given in Table 3.1. The regression models for each treatment are plotted together with the measured fluxes in Fig. 3.3.

All regression lines in the model are forced through an intercept of 5 °C, assuming that there is no significant microbial activity below this temperature (Boon and Mitchell, 1995). This was done by subtracting 5 degrees from the measured temperature and excluding an intercept in the model. With this model, including the 3 regressions, the F value is 84.2 ($p < 0.001$) and the effect size (η^2) 0.869. The control treatment showed the highest flux and CR treatment the lowest. The slope of the control treatment is about twice as high as that of the other treatments (see Table 3.1) ($p < 0.001$), but the slopes of CR and CSR are not significantly different from each other ($p = 0.359$).

Table 3.1 Descriptive statistics and slopes (beta) with significant levels for the different treatments in the ANCOVA model. The interaction is (Chamber temperature – 5) * Treatment

Treatment	N	Mean	SD	Beta Interaction*	Sig
CR	17	300.5	289.6	14.7	0.000
CSR	9	370.7	649.4	19.0	0.000
Control	15	792.2	508.7	35.1	0.000

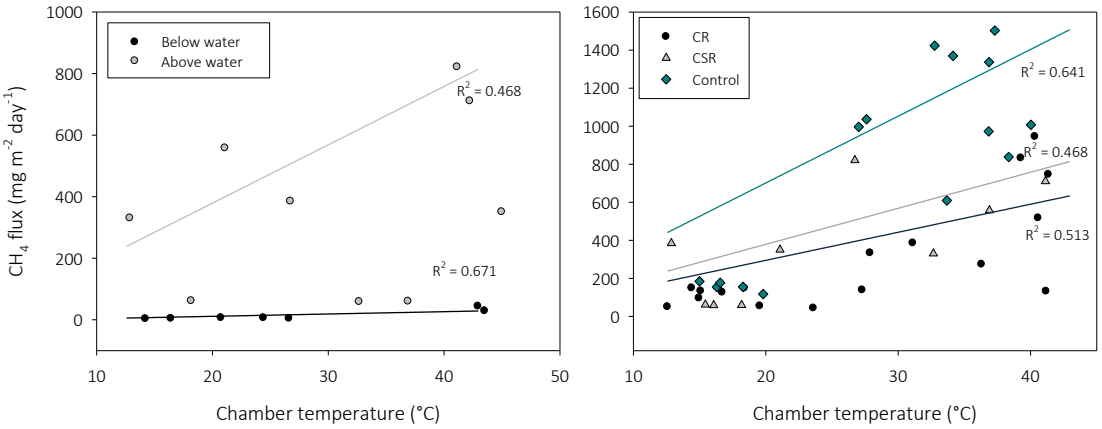

Fig. 3.3 CH_4 flux in relation to chamber temperature. Left: the treatment clipped and sealed reed (CSR), in black the measurements in the plot with the stems below water (7 June) and in grey the plots with stems above water (9 June, 10 June). Right: all treatments (clipped reed (CR), clipped and sealed reed (CSR) and control) excluding the measurements from CSR with stems below water. The linear regression models are all significant ($p < 0.001$).

3.3 4 EBULLITION

The volume of trapped ebullition gas from the soil differed between the treatments and control: CR and CSR have a 2 to 3 times higher release of ebullition gas than the control (76 ml m^{-2} day^{-1}) (Fig. 3.4). The difference between CSR and control is significant ($p < 0.05$). For the CH_4 volume both treatments are significantly different from the control ($p < 0.05$), but not significantly from each other. In both CR and CSR treatments, CH_4 is clearly dominating ebullition: the percentage of CH_4 in the ebullition gas was around 4 to 5 times higher in the CR (51%) and CSR (71%) treatments compared to the control (13%). Zero (CR and CSR plots) or very low amounts (0.6 ml m^{-2} day^{-1}) (control plots) of N_2O were found in the ebullition traps. To compare the ebullition flux with the total flux, we calculated the average daily chamber flux based on the temperature model

(Fig. 3.3). The fluxes were calculated for a temperature of 14.7 °C, which is the average ambient temperature from 7 to 27 June (the period in which ebullition gas was captured). The fraction of ebullition is 13 to 16 times smaller in the control than in the CR and CSR treatments (Table 3.2).

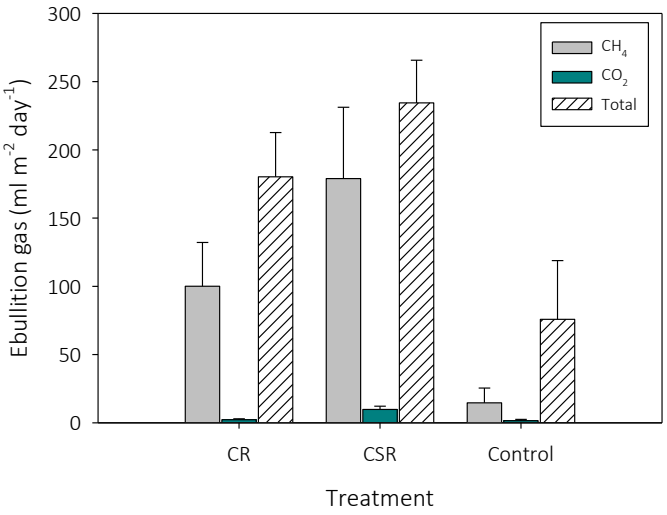

Fig. 3.4 Means of trapped ebullition gas over 18 days per treatment. The error bars are the standard errors of the means (N=3). Total volume of gas is composed of mainly CH_4 (light grey bars) and CO_2 (dark grey bars). The total volume is presented in white striped bars.

Table 3.2 The chamber flux, ebullition flux and total flux (sum of chamber and ebullition flux) compared as fraction ebullition/chamber flux.

Treatment	CH_4 chamber flux mg m^{-2} day^{-1}	CH_4 ebullition flux mg m^{-2} day^{-1}	Total flux mg m^{-2} day^{-1}	Fraction ebullition/total flux
CR	217	71	288	0.25
CSR	279	126	405	0.31
Control	517	10	527	0.02

3.3.5 $\delta^{13}C$ CHANGE FROM SOIL CH_4 TO EMITTED CH_4

In all treatments the CH_4 sampled in the chamber show lower $\delta^{13}C$ than CH_4 from ebullition (Table 3.3). The largest depletion was found for CR, followed by CSR and control.

Table 3.3 $\delta^{13}C$ measured in ebullition and chamber flux. The difference is a measure of the fractionation due to oxidation or gas transport pathways.

Treatment	Chamber flux		Ebullition		$\delta^{13}C$ change
	$\delta^{13}C$	st.error	$\delta^{13}C$	st.error	
CR	-62.21	1.44	-50.93	1.59	-11.28
CSR	-63.05	1.53	-55.95	0.87	-7.10
Control	-60.35	1.29	-55.44	1.46	-4.91

3.4 DISCUSSION

3.4.1 INFLUENCE OF *PHRAGMITES* ON CH_4 FLUXES

The total CH_4 flux (chamber + ebullition) decreased with 45% and 23% when we clipped the reed (CR) and clipped and sealed the reed (CSR), compared to intact reed (control). van der Nat et al. (1998) also found a lower CH_4 flux from water saturated bare soil compared to *Phragmites*-vegetated soil, only with a difference of 75%. Our findings are, however, contradicting with the findings of Grünfeld and Brix (1999). They showed in an experiment a 34% lower CH_4 emission with *Phragmites* in a submerged organic soil compared to the same soil without *Phragmites* and argued that methanogenesis is reduced and CH_4 oxidation increased because of the transport of oxygen by *Phragmites* into the rhizosphere. In the soil without reed, the gas transport would be dominated by ebullition. The reason for the different findings of Grünfeld and Brix compared to our data, could be because the experiment was conducted with single *Phragmites* seedlings (6 months old) and CH_4 was measured 9 weeks after planting. This means that there was no rhizome network present as in a normal reed bed. Because CH_4 is taken up by the rhizomes and transported upwards, it could be that the amount of CH_4 transport was lower than at our site. Probably the oxygen transport to the soil is not much limited by reduced rhizomes. However, we did find a clear increase in the ebullition in the CR and CSR treatments, the percentage of ebullition to the total flux is the highest for CSR (37%), followed by CR (24%), and much lower for the control plots (2%). This large influence of vascular plants on the amount of ebullition was also shown by van der Nat et al. (1998). In an experiment they found that in unvegetated soil (compared to *Phragmites* vegetated soil) ebullition was the main gas transport pathway, while in a *Phragmites*-vegetated soil more than 98% of the CH_4 was transported through the reed. Despite the higher ebullition from CR and CSR treatment, the increase does not compensate the excluded pathway via the pressurized air flow.

CR only showed slightly lower chamber flux than CSR (217 vs 279 mg m^{-2} day^{-1}), indicating that sealing the stems hardly affected the chamber CH_4 flux (disregarding ebullition) much. Only the

CSR plots with stems below water (see Material & Methods) showed a clear reduced CH_4 flux compared to plots with stems above water. This suggests that our sealing method was not fully effective. Possibly gas could still escape from, for example, cracks in the stem. Emission from ebullition in CR was, however, 40% less than in CSR. Although not statistically significant, this may indicate that the sealing probably affected transport pathways in the following way: in CR a larger part of the gas was transported via the stems while in CSR more gas was transported via diffusion and ebullition from the soil. It is also possible that in CSR there was less O_2 transport due to the sealing and therefore lower CH_4 oxidation and/or higher CH_4 production rates in the soil. The assumption of lower O_2 transport is supported by the high DOC concentration in CSR in 30 cm depth, suggesting that roots died off due to a lack of O_2 which would result in a higher release of DOC.

CR and CSR reduce or exclude plant-mediated gas transport, but fluxes are not directly comparable to those from bare soil. In CR roots and clipped stems still allowed gas transport via diffusion, but not via pressurized flow as in the control plots. The clipped stems act as chimneys that connect deeper soil layers to the atmosphere. In line with this, Greenup et al. (2000) found that CH_4 flux from *Sphagnum* vegetation increased after inserting glass tubes into the soil. Despite this chimney function, we found that fluxes from clipped reed were small compared to the control, indicating the major role of pressurized flow in intact reed beds.

3.4.2 PLANT MEDIATED TRANSPORT

Reed strongly influences CH_4 fluxes. Fluxes from clipped reed were 2 times lower, based on their temperature dependency (see Fig. 3.3), than fluxes from intact reed. The $\delta^{13}C$ signature change shows the difference in the gas transport mechanism between clipped and unclipped *Phragmites* as well. Without considering $\delta^{13}C$ signature change due to gas transport, emitted CH_4 is expected to be enriched with ^{13}C compared to produced CH_4, since part of the CH_4 is oxidized. This would result in a positive $\delta^{13}C$ signature change. We found the opposite: the $\delta^{13}C$ depletion was larger in the CR and CSR treatments (-11‰ and -7‰ respectively) than in the control (-5‰). This decrease in $\delta^{13}C$ signature in CR and CSR is in the same range as in CH_4 emission from plants with diffusive gas transport (Chanton et al., 2002). That clipped vegetation can be considered as plants with diffusive gas transport, is in line with the findings Greenup et al. (2000). They did not find a significant difference between CH_4 flux from clipped stems of *E. vaginatum* above the water table and from unclipped vegetation. Gas transport in *E. vaginatum* is known to be due to diffusion.

The lower fractionation of CSR compared to CR treatment can be explained by the fact that gas transport through the stems is partly limited due to the sealing in the CSR treatment. Chanton (2005) compared $\delta^{13}C$ change from soil to atmosphere from different wetland plants and found,

on average, a smaller change for plants with convective transport than for those with diffusive transport. That corresponds to our results.

With respect to the assumption that gas transport in clipped reed is diffusive, we can summarize that pressurized CH_4 transport in intact reed leads to a CH_4 emission 2 times that of clipped reed with diffusive transport through culms.

3.4.3 CHAMBER METHOD VS EDDY COVARIANCE METHOD

The inherent temporal and spatial heterogeneity of soils and vegetation is one of the main reasons why studies comparing CH_4 fluxes from EC measurements with direct measured fluxes with chamber are rare. The chamber method measures fluxes at a scale of a square meter. The footprint of an EC station, depending on the sensor installation and canopy height, is in the range of several hundreds of square meters. This becomes particularly precarious in heterogeneous landscapes (Hendriks et al., 2010; Schrier-Uijl et al., 2010; Godwin et al., 2013; Sun et al., 2013; Krauss et al., 2016). The EC footprint of our site is very homogeneous in regard to vegetation and landscape development (see *Study site*). Thereby, ebullition makes up for only a small percentage of the total flux. This contributes to a more constant flux without abrupt and random emission peaks of CH_4. Temporal homogeneity could also make comparison difficult. If data are scaled up to a daily fluxes, (night-time) emission events or lower emission rates might be missed with the chamber method (Hendriks et al., 2010; Godwin et al., 2013; Podgrajsek et al., 2014; Krauss et al., 2016). Therefore, measurement duration and timing is important when the chamber method is applied. Our chamber measurements show very similar diurnal patterns as EC measurements, with low fluxes in the morning and simultaneous increases when light intensity and temperature increased. The highest discrepancy between chamber and EC fluxes were found within 10 minutes after ventilating. Lifting the chambers and placing them back has likely caused disturbances. Apparently, it takes several minutes before CH_4 production and emission are in equilibrium again. In a lab experiment Christiansen et al. (2011) found indeed a 35 % reduction in the first flux after placing the chamber compared to a reference flux. The fact that not all first measurements after ventilating resulted in a discrepancy, can most probably be explained by the differences in time between ventilating and the measurement (between 1-15 minutes).

Another reason for differences between the chamber and EC methods could be the difference in internal chamber conditions, like temperature, pressure and atmospheric turbulence, compared to ambient conditions. This is especially a problem with CO_2 fluxes (Davidson et al., 2002; Balogh et al., 2007; Riederer et al., 2014), probably because photosynthetic rates directly respond to changing conditions. Chamber conditions are also thought to cause differences between the methods of CH_4 flux measurements (Yu et al., 2013). In our wetland system it appears that

internal chamber conditions did not influence the CH_4 flux much, despite the large contribution of plants to the CH_4 transport from the soil. We observed a much larger discrepancy between the methods with CO_2 fluxes (data not shown).

3.4.4 CONCLUSIONS

Comparing CH_4 fluxes measured with the EC and the chamber method, we show similar results with respect to magnitude and diurnal patterns. We conclude that the chamber method yields representative CH_4 fluxes for the whole system.

Excluding pressurized flow in *Phragmites* by clipping the stems, reduced the CH_4 flux (without ebullition) by about 60%. On the other hand, ebullition increased by a factor of 13. When ebullition was added to the chamber flux, the intact reed still had the highest total CH_4 flux. This means that the increase in ebullition does not compensate for the exclusion of pressurized air flow. It also means that the effect of CH_4 bypassing of the oxic water layer due to plant transport is much larger than the effect of O_2 transport by the plants on CH_4 oxidation and production in the rhizosphere. Overall, this shows that plants with pressurized gas transport mechanism are an important contributor to CH_4 emission from wetlands.

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Chapter 4

Water and energy fluxes from a *Phragmites* fen in southwest Germany

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ABSTRACT

Phragmites australis is expected to have a high evapotranspiration (ET) rate due to the large leaf area, open water habitat, and high aerodynamic roughness. Measured ET with the eddy covariance (EC) method in a *Phragmites* fen was evaluated in perspective of energy partitioning. The measured ET data were used as well to derive crop factors to come from FAO's Penman-Monteith reference ET (ET_o) to crop ET (ET_c). We used 3 approaches for the crop factor calculation: 1) monthly averages; 2) one crop factor for wet and one for dry days; and 3) a regression model to calculate daily crop factors. We compared our results with crop factors from literature.

During the growing season in 2013 and 2014, measured mean ET from this *Phragmites* fen (1.3 and 2.0 mm day^{-1}) was much lower than expected from literature. Especially in May and October, when plant activity was low, the dominant energy flux was sensible heat (H) not latent heat (LE) with an average Bowen ratio larger than 1.5. This can be explained by the dense dead reed that heats up causing a high H. The low evaporation was due to the shading of the water layer below the canopy and low wind velocities near the surface.

From the crop factors used from literature, Zhou and Zhou (2009)'s regression model yielded the best results. The regression model, based on measured air temperature, air relative humidity, and net radiation, resulted in crop factors with similar day-to-day fluctuations as crop factors based on measured ET. Therefore, the model of Zhou and Zhou is an interesting and robust approach to estimate daily K_c values and can be recommended.

4.1 INTRODUCTION

Globally, wetlands have a total surface area of around 9 million km^2, which is about 7% of the land surface (Mitsch and Gosselink, 2007). They are important ecosystems due to the high biodiversity, the ability to store carbon, and their function as water resources (Mitsch and Gosselink, 2007). All these characteristics depend on the hydrology of the system. In a natural wetland, rainfall and evapotranspiration (ET) dominates the water balance. The largest part of the total available solar energy is generally used to evaporate and transpire water (Priban and Ondok, 1985; Acreman et al., 2003). Another factor affecting ET is the change in vapor pressure, and all factors that are related to this, such as air temperature, relative humidity and wind speed (Bonan, 2008). Also plants play an important role. Wetland plants can transpire much water since there is no water shortage. The transpiration rate depends on the developing stage of the plant (Allen et al., 1998) and differs per species (Burba et al., 1999, Pauliukonis and Schneider, 2001, Anda et al., 2015).

Phragmites australis (common reed), is a widely abundant wetland plant and can be found on every continent on earth (IUCN). *Phragmites* is expected to have a high ET rate due to the large leaf area, open water habitat, and high aerodynamic roughness (Acreman et al., 2003). There is the evidence that ET from reed areas could exceed open lake evaporation (Burba et al., 1999; Herbst and Kappen, 1999; Borin et al., 2011) and even the yearly precipitation (Herbst and Kappen, 1999), which could eventually cause a wetland to dry out. In the USA, the European subspecies *Phragmites australis* is being controlled with the aim to reduce ET so that there is more water available for human uses like irrigation (Mykleby et al., 2016). This makes it relevant to quantify the amount of ET from *Phragmites* dominated wetlands.

There is much variation in ET data from different *Phragmites* wetlands worldwide. This variation can be explained by the differences in weather conditions but also by the different measurement or estimation methods used (for an overview see Mykleby et al., 2016 and Anda et al., 2015). In temperate regions, the range of ET during the growing season is around 3 mm day^{-1} (England, Peacock and Hess, 2004; Fermor et al., 2001); in a Mediterranean climate up to about 30 mm day^{-1} were measured (Italy, Borin et al., 2011). Most of the studies made use of lysimeters or the water balance method. The problem of these methods lies in the disturbance of the measurement areas. The eddy covariance (EC) method is the most direct measurement method for capturing ET without disturbing the area of interest. This measurement technique makes it also possible to gather data in a high temporal resolution. Nevertheless, not many studies have been done with this method, probably because reed areas are mostly too small to cover the footprint (source area) of the flux measurement with EC.

It is also possible to calculate ET with the widely used Penman-Monteith equation. The calculation is based on a combination of thermodynamic and aerodynamic aspects of ET. A simplified version is FAO's Penman-Monteith model (Allen et al., 1998), where surface resistance and parameters of the aerodynamic resistance are fixed to a reference crop (grass), so that only meteorological data are needed for the calculation. To come from the reference ET (ET_o) to the actual ET, ET_o is multiplied with a crop factor (K_c). K_c values are gained from studies that compare measured ET with calculated ET_o. There are several approaches to come to K_c values, we selected 3 of them to compare it to our measured data; 1) Anda et al, (2015), calculated average K_c values per month; 2) Peacock and Hess (2004) calculated two K_c values, distinguishing between wet and dry days; and 3) Zhou and Zhou (2009) set up a regression model with temperature, net radiation and relative humidity as independent variables to calculate daily K_c values.

In our study we measured ET with the EC method in a 2.2 km^2 reed belt. The measurement area is part of the largest peatland of southwest Germany. We evaluate the ET fluxes and put them in the perspective of solar energy partitioning. We also compare our direct measurements with the FAO Penman-Monteith method. The different approaches to calculate K_c values from literature will be elaborated and discussed.

4.2 MATERIAL & METHODS

4.2.1 RESEARCH AREA

The Federseemoor is a peatland of 30 km^2 in southwest Germany in the region Upper-Swabia. The largest part is highly influenced by human activities, like peat excavation and ground water lowering to create agricultural land. The central part of around 11 km^2 is a nature conservation area with a lake of 1.4 km^2 (Federsee) in the middle. The lake is surrounded by reed vegetation (*Phragmites australis*). The reed covers a surface of 2.2 km^2 and has a density of around 70 living shoots m^{-2}. The reed belt is 30 to 400 m broad, and at the broadest part the eddy covariance tower was set up. The high density and the lack of species other than *Phragmites australis* in the reed belt, makes the area very homogeneous and thus perfect for the EC method. A large part of the Federseemoor, including the reed area, is part of the European Union's nature protection areas network.

4.2.2 EDDY COVARIANCE

The location for the EC station was chosen such that exclusively reed vegetation was in the fetch (potential footprint). A footprint analysis revealed that always 90% of the measured gas had its source within the distance of 200 m from the tower.

On a tower of 6 m height, twice as high as the vegetation canopy, an LI-7200 enclosed CO_2/H_2O gas analyzer (LI-COR Inc., USA) and a WindMaster Pro ultrasonic anemometer (Gill Instruments Ltd., UK) were installed.

Fluxes were calculated for every 30 minutes using the Eddypro software version 6.1.0 (LICOR-inc, USA). The anemometer appeared to have a software bug affecting the vertical wind component. According to the Technical Key Note of the manufacturer, this bug can be corrected with the declination of the angle-of-attack correction according to Nakai and Shimoyama (2012). We applied this correction to our data. To correct the tilt of the anemometer or angle of the mean horizontal wind, the double rotation method was applied (Wilczak et al., 2001). The calculated fluxes were checked for quality by means of the 1-9 flagging system of Foken et al. (2004). Only fluxes with quality flags 1-6 were used for further data processing. Outliers were filtered out by removing fluxes that were more than 4 times the median within a time window of 6 hours and with six or more data points within this time window.

Gap filling for latent (LE) and sensible (H) heat flux was done with the R script of the Max Planck institute of Biogeochemistry in Jena, which is based on the look-up table method (Falge et al., 2001; Reichstein et al., 2005). The best correlations were found between LE and available energy (net radiation – ground heat flux) ($r = 0.865$), air temperature (Ta; $r = 0.618$) and vapor pressure deficit ($r = 0.664$). These variables were used as input variables for the look-up table. The sensible heat flux was only correlated with available energy ($r = 0.924$), which is thus the only variable used for gap filling.

4.2.3 ENVIRONMENTAL VARIABLES

Ta, air relative humidity (RH) (HMP155, Vaisala Inc., Finland), incoming and outgoing shortwave and longwave radiation (CNR4, Kipp & Zonen Inc., The Netherlands) were measured at 6 m height. Soil temperature was measured in 0.05, 0.15 and 0.30 m depth (LI-COR Inc., USA). Water table was continuously measured with a groundwater datalogger (MiniDiver, Eijkelkamp Agrisearch Equipment Inc., The Netherlands). Rainfall (TR-525USW, Texas Instruments Inc., USA) was measured at 3 m height. These environmental variables were measured every minute and averaged over 30 minutes, with exception of the water table height, which was measured every 30 minutes. Vegetation height was measured weekly.

To calculate the 5-year averages (2008-2012) of Ta, water table height and precipitation, data were obtained from different sources. In 2.2 km distance from our EC station, a meteorological station is operated by the Federal State of Baden-Württemberg (LUBW). Temperature measured every 15 minutes from this location was used. Water table height is measured daily by the local nature protection organization (NABU-Federsee) at the water outlet of the lake. Daily measured precipitation was obtained from the Wetterwarte-Sued website (local German weather service) measured in Bad-Schussenried (around 10 km distance from the EC station).

4.2.4 ENERGY BALANCE AND POST-CLOSURE UNCERTAINTY BAND

The difference between incoming and outgoing longwave and shortwave radiation at the earth surface is called net radiation (Rn). This Rn is mostly partitioned into 3 main components: latent heat flux (LE), energy related to the evaporation of water; sensible heat flux (H), energy related to temperature change of the air; and ground heat flux (G), energy related to temperature change of the soil. The ratio of H and LE (H/LE) is called the Bowen ratio. It can be seen as a measure for the wetness or aridity of a system (0.1-0.3 for rainforests to 2-6 for semi-arid systems, Bonan, 2008). Neglecting minor fluxes and storage terms the energy budget at the land surface is described as: $Rn = LE + H + G$.

It appeared that when measuring LE and H with the EC method, the energy balance is usually unclosed (Foken, 2008b), $Rn - G$ (called the available energy) is larger than the sum of the turbulent fluxes LE and H. The residual $(Rn - G) - (LE + H)$ is called the energy gap, or what is described by the turbulent fluxes is called the energy balance closure (EBC). Both energy gap and EBC are expressed as percentages of the available energy. This imbalance is a longstanding problem and a well-known source of uncertainty in EC measurements. Neglecting the minor fluxes and the storage terms, the missing energy may be uncaptured LE or H fluxes (or both). Since it is unclear what exactly the cause is of this imbalance, Ingwersen et al. (2015) proposed to express the uncertainty of measured LE by adding a post-closure methods uncertainty band (PUB), with the measured LE as lower limit and the sum of LE and energy gap as upper limit (Ingwersen et al., 2015). The real LE should be within this uncertainty band.

4.2.5 LEAF AREA INDEX

In 2014, between 22 May and 18 October, leaf area index (LAI) was measured weekly with an LAI-2000 plant canopy analyzer (LI-COR Inc., USA) (Fig. 4.1). Four different locations close to the EC tower were chosen to measure LAI, and averaged. Some measurements were removed due to rainfall or bright sunlight. There were no LAI measurements for 2013. We assumed that LAI was the same as in 2014, since the start of the vegetation was only 3 days earlier, and vegetation

height reached its maximum of 2.5 m in mid-July. Thereby, the average temperature over the whole season differed only by 0.3 °C between the 2 years.

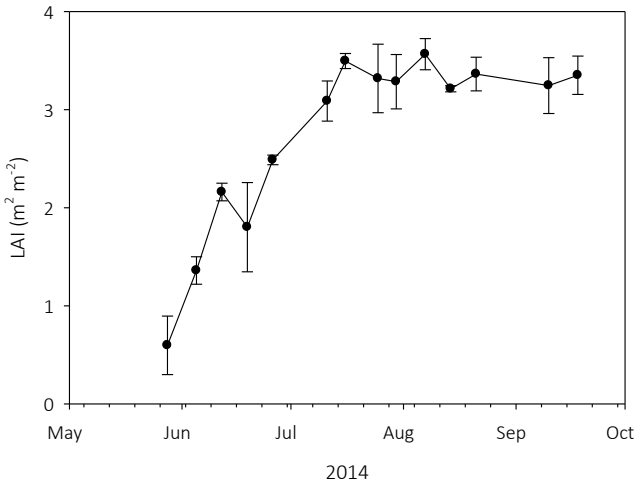

Fig 4.1 Leaf area index (LAI) measured in 2014. Every point is an average of 4 measurements. Error bars depict standard errors.

4.2.6 GROUND HEAT FLUX

Ground heat flux (G) was calculated based on soil temperature by applying harmonic wave analysis (Horton et al., 1983). This method considers the change of temperature as being caused by heat waves that move through the soil. These waves have different frequencies (from hour to season) and the amplitudes of the waves are exponentially dampened with increasing soil depth. Also the phase of the waves is shifted with increasing soil depth. Dampening and phase shift are frequency-dependent. The dampening is quantified by the dampening depth (D_n). It is inversely related to the exponential decrease of the amplitude with increasing depth. D_n was calculated for periods of 24 hours (diurnal fluctuation) from soil temperature measurements at 0.05, 0.15, and 0.30 m depth. Five clear-skied days over the whole season of 2014 were selected to determine the amplitude in every depth and the exponential decrease for each day, resulting in an average D_n of 0.1049 m^{-1}. Soil temperature measured in depth (z) can be transformed to the frequencies with amplitudes and phases with the Fast Fourier Transformation. With the known D_n, the amplitudes and phases of all frequencies can be transformed to come to the surface temperature (see Horton et al., 1983 for a detailed description). Then the ground heat flux is:

$$G(z,t) = -\lambda \frac{\delta T(z,t)}{\delta z} \quad (4.1)$$

where $\delta T/\delta z$ is the temperature gradient over depth z at time t, and λ (W m^{-1} K^{-1}) is the ground heat conduction coefficient. λ can also be written as $\kappa * C_v$, with κ as thermal diffusivity and C_v as volumetric heat capacity. The volumetric heat capacity (C_v) of $3.89 \cdot 10^6$ J m^{-3} K^{-1} was taken from (Foken, 2008a) (swamp, 90% water), and κ was calculated from the damping depth:

$D_n = \sqrt{2\,\frac{\kappa}{n\omega}}$, with ω being the frequency and n a certain period.

A difficulty with this analysis is the assumption of a fixed measurement depth for temperature, because at our site a fluctuating water table was present above the soil surface. Therefore, first the temperature on the border between soil and water was calculated by the harmonic wave analysis. The resulting temperature was used as input to calculate G on the water surface with the harmonic wave analysis, by using the following parameters: D_n = 0.0760 m^{-1} and $C_v = 4.08 \cdot 10^6$ J m^{-3} K^{-1} were used. These parameters are between that of pure water (D_n: 0.0615 m^{-1} James, 1968 and C_v: $4.18 \cdot 10^6$ J m^{-3} K^{-1}) and of swamp soil and selected because the water layer layer contains much organic material such as dead reed.

When water table height exceeded 6 cm above ground, the harmonic wave analysis was not accurate anymore. In this case, missing data were calculated by regression. The ground heat flux G was regressed on net radiation and air temperature. Regressions were constructed month by month using 30-minutes flux data. In July, September and October 2013 the water table was too high to be able to calculate G by regression. Therefore this period was not considered in the calculations.

4.2.7 EVAPOTRANSPIRATION CALCULATED WITH FAO METHOD

For comparison with measured ET, ET was calculated with FAO's Penman-Monteith equation (eq. 4.2) (Allen et al., 1998). Based on a reference crop (well-watered grass with 12 cm height, with a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23), the Penman-Monteith equation reads:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{18.75}{T+273} u_2\,VPD}{\Delta + \gamma(1 + 0.34\,u_2)} \qquad (4.2)$$

Here, ET_o is in mm, R_n in MJ m^{-2} (30 min^{-1}), G in MJ m^{-2} (30 min^{-1}), T is temperature in °C, u_2 wind speed in 2 meters above ground in m s^{-1}, VPD vapor pressure deficit in kPa, Δ slope of the vapor pressure curve in kPa $°C^{-1}$, and γ the psychrometric constant in kPa $°C^{-1}$. The value 0.408 is a constant to convert MJ m^{-2} to mm. Our wind speed and humidity measurements were done at 6 m height, while the FAO assumes a measurement height of 2 m. Since the measurement height is influencing the aerodynamic resistance (r_a), we used Eq. 4.3 to correct the wind speed.

$$r_a = \frac{Ln\left[\frac{z_m - d}{z_{om}}\right] ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z} \qquad (4.3)$$

where z_m is the height of wind measurements in m, z_h is the height of humidity measurements in m, d is the zero plane displacement height (2/3 times canopy height) in m, z_{om} is the roughness length of momentum transfer (0.123 times canopy height) in m, z_{oh} is the roughness length of the transfer of heat and vapour (0.1 z_{om}) in m, k is the von Karman's constant (0.41), and u_z is the wind speed at height z in m s^{-1}. For the reference crop r_a equals $208/u_2$. We calculated r_a for canopy height of the reference crop (0.12 m) and measurement height of 6 m, and come to an r_a of $295.6/u_z$. The wind speed was then corrected with the factor 208/295.6 = 0.70.

To come from reference evapotranspiration (ET_o) to crop evapotranspiration under well-watered conditions (ET_c), ET_o is multiplied with the crop coefficient K_c. Since this wetland does not encounter water stress, there is no need in considering extra stress coefficients. In the literature we found three approaches to calculate K_c factors for *Phragmites* wetlands: monthly averages (Anda et al., 2015); two K_c values for wet and dry conditions (Peacock and Hess, 2004) and a regression model to calculate daily K_c values (Zhou and Zhou, 2009). Finally, K_c values or model described in the literature were compared with K_c values calculated from our data using the same approaches.

Anda et al. (2015) calculated monthly values of K_c, different for cool, normal and warm conditions, based on a data-set of 6 seasons. We used the values for cool conditions, since these were in the same temperature range as measured at our site. At our site the growing season started one month later than at the site of Anda et al. (Hungary), so we used the K_c values shifted by one month. Further, we derived own monthly K_c values by regressing daily mean ET_o on measured ET with no intercept. Peacock and Hess (2004) calculated two K_c values in England, separately for dry days (0.53) and for rainy days (>0.1 mm rain) (0.88), by comparing calculated ET_o with measured ET using the Bowen ratio method at a location, We did the same for our data.

Zhou and Zhou (2009) tackled the problem of day-to-day variation in K_c values, and related these variations to environmental variables (Rn, Ta and RH). Regression analysis yielded the following equation for daily K_c values per day:

$$K_c = (aR_n + 1)(bT_a{}^2 + cT_a + 1)(d\ e^{xRH}) \quad (4.3)$$

Here, Rn is given in MJ m^{-2} day^{-1}, T_a in °C and RH in %. Zhou and Zhou estimated the following values for the parameters: a = -0.033, b = 0.006, c = 0.012, d = 0.213, e = 0.004. We calculated daily K_c values with this model and parameter set, and fitted the above model to our measured data and calculated the related K_c values.

Finally, we compared these three approaches. The agreement beween ET_c and measured ET (ET_{EC}) was evaluated by the root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \quad (4.4)$$

Here, $\hat{y}$ is ET_c and y ET_{EC}.

4.3 RESULTS

4.3.1 ENERGY FLUXES

The average temperature during the growing season (May-October) was 13.9 °C in 2013 and 14.2 °C in 2014. The vegetation development showed a similar pattern in both years: reed started to grow from the beginning of May, was fully grown in July where it reached a height of 2.5 m with a leaf area index (LAI) of 3.5, and slowly got into the senescence stage by the end of September.

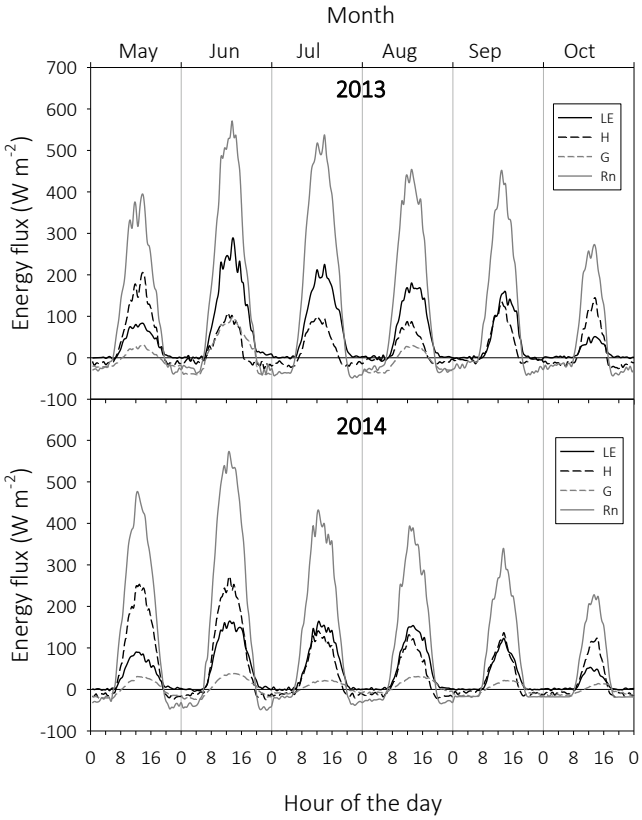

Fig. 4.2 Average diurnal energy fluxes per month in 2013 (above) and 2014 (below). Rn stands for net radiation LE for latent heat flux, H for sensible heat flux and G for ground heat flux.

The Bowen ratio changed during the season with the different plant growth stages (Table 4.2). In May and October of both years, H was larger than LE (Fig. 4.2), with in every month an average Bowen ratio larger than 1.5 (even 2.4 in May 2014) (see Table 4.2). This large Bowen ratio is caused by a remarkable large H in May (average of 65 W m^{-2}), while in October a small LE (12.8 to 18.7 W m^{-2}) is responsible for the high Bowen ratio (see Fig, 4.3A and 4.3B). During summer,

when the reed was fully grown and green and Rn reached its maximum, LE increased while H decreased, and LE became larger than H. In 2014, the Bowen ratio during the summer months (June-September) was much higher than in 2013 (Table 4.2). This difference between the two years can be explained by the higher water table in June, and the higher temperature in July and August of 2013 (see Table 4.1)

Table 4.1 Temperature, height of water table (above surface) and rainfall in the measurement years expressed as difference to the 5-year average (2008-2012).

Month	Temperature °C			Water table cm			Rainfall mm		
	Average	Difference		Average	Difference		Average	Difference	
	5-years	2013	2014	5-years	2013	2014	5 years	2013	2014
May	11.0	-1.4	0.9	6.7	0.9	-1.1	120	5	-65
Jun	14.7	0.5	1.8	9.3	13.4	-5.3	144	-23	-72
Jul	16.3	2.7	1.0	13.8	-4.5	-6.8	155	-134	-10
Aug	16.6	0.3	-1.4	16.1	-7.0	-6.7	106	-55	10
Sep	11.8	1.2	1.7	12.2	-1.2	-4.6	73	25	-7
Oct	7.4	2.2	3.6	11.2	-0.8	-1.1	62	27	11

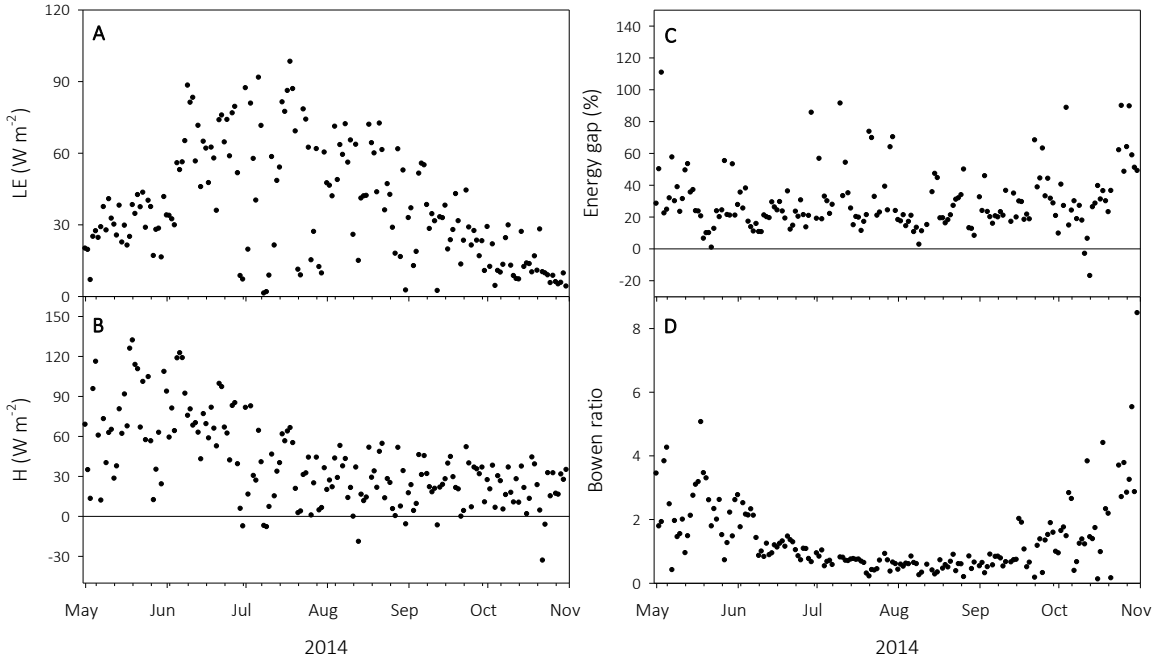

Fig. 4.3 Daily averaged energy fluxes from May to November 2014 with A) latent heat flux; B) sensible heat flux; C) energy gap Rn – G = LE + H; D) Bowen ratio, H / LE. For the Bowen ratio, only data are shown when both LE and H fluxes are > 0.01*MAX, since small number could result in large outliers for the Bowen ratio.

Table 4.2 Average Bowen ratio and energy balance closure relative to net radiation mines ground heat flux (Rn-G) in the growing season (May-October) in 2014.

	Bowen ratio		EBC (%)	
Month	2013	2014	2013	2014
May	1.81	2.41	68.7	76.5
June	0.26	1.32	75.4	80.4
July	0.28	0.69	60.9	71.7
August	0.33	0.57	55.1	77.9
September	0.64	0.90	64.4	72.2
October	1.56	1.68	60.0	66.0
Average	0.81	1.26	64.1	74.1

4.3.2 FAO'S PENMAN-MONTEITH ET

For the ET calculation with the FAO method, only data for 2014 are used, because of missing ground heat flux data in some months in 2013 (see section 4.2.6). Monthly K_c values were obtained by regression (Fig. 4.4). The models vary in their parameters and their coefficient of determination (R^2), with highest slopes and best fits in July and August. All monthly K_c values calculated from measured data are clearly lower than the K_c from (Anda et al., 2015) (Table 4.3). This causes the relative large discrepancy of ET_c compared to ET_{EC} compared to the results from our monthly calculated K_c values (Fig. 4.5). Peacock and Hess (2004) found that the main difference in K_c values over a growing season could be traced back to differences in rain days (>0.1mm, K_c = 0.88) versus dry days (K_c = 0.53). In our data, we found no significant difference for rainy and dry days (0.52 and 0.49 respectively). To see if this difference changes over the season, we compared separately monthly K_c values for rainy and dry days. The difference was then only significant in May ($p < 0.05$), and in July the difference in K_c value was the opposite, higher for dry days than for rainy days (0.71 versus 0.59). So this does not support the consistent difference in dry and rainy days. (Zhou et al., 2009) created a regression model (see eq. 4.4, section 4.2.7) to calculate daily K_c values. Fitting the same model to our data, a parameter set was created with a = -0.018, b = 0.002, c = 0.051, d = 0.276, and e = 0.001. This parameter set slightly increased the fit to the measured data (RMSE of 11.6 compared to 13.0; see Fig. 4.5). Because the aim of (Zhou et al., 2009) was to get daily accurate K_c values, the modelled data were compared with daily calculated K_c values from ET_{EC} over time (Fig. 4.6). Except for the month August, the modelled K_c and K_c values calculated from ET_{EC} show a very similar pattern and have the same magnitude. Compared to the K_c values calculated with the model of (Zhou et al., 2009), the other K_c values from literature resulted in an over-estimation on average. With Kc values calculated from our own data, the monthly calculated K_c values resulted in the best agreement of ET_c to ET_{EC} (lowest RMSE) and rainy days and dry days K_c values in the least agreement (see Fig. 4.5).

Table 4.3 Monthly Kc values after Anda et al. (2015) and calculated from ET measured by EC (Fig. 4.3).

Month	K_c (Anda et al.)	K_c (ET_{ec}/ET_o)
May	0.80	0.32
June	0.62	0.45
July	0.72	0.59
August	0.77	0.70
September	0.80	0.57
October	0.60	0.40

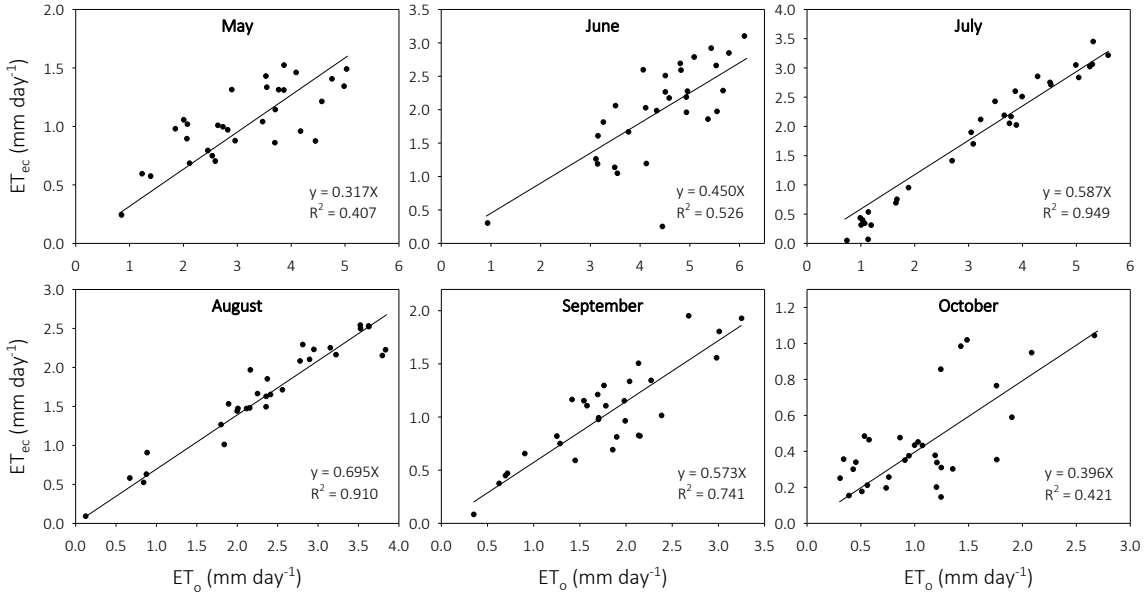

Fig. 4.4 Regression of monthly K_c values from daily mean measured ET (ET_{ec}) on daily reference ET (ET_o) from the FAO.

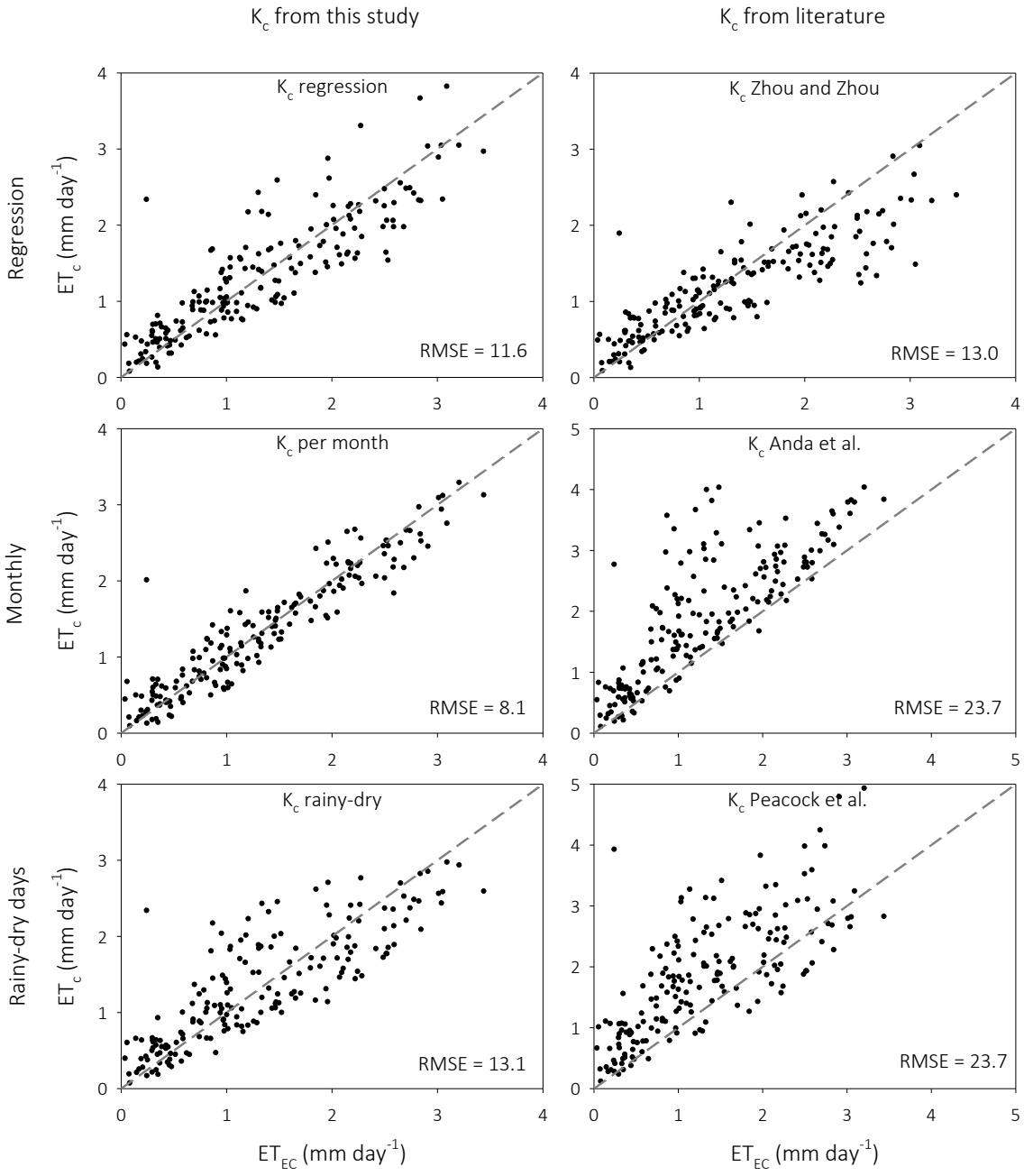

Fig. 4.5 Model performance with different Kc values, calculated with three different methods (regression, monthly mean, dry-wet days)

Zhou and Zhou's model with their parameters results in the lowest K_c values, and the cumulated ET_c from Zhou & Zhou is just below the PUB, which means it is slightly underestimating actual ET. The cumulative ET_c with K_c values from Anda et al. and Peacock and Hess were much further from ET_{EC} (lower limit of PUB) but always within the PUB (Fig. 4.7). The total rainfall of 535 mm is more than twice as large as ET_{EC} (242 mm). Even the maximum possible ET (upper band of PUB) is below the total rainfall. In 2013, 36% of the available energy was not detected as turbulent fluxes, which is equal to 55 W m^{-2} and in 2014 26% of the available energy remained undetected, on average

37 W m^{-2}. If all missing energy from the energy gap is added up to LE, the cumulative ET in the growing period increases to 357 mm in 2013 and to 239 mm in 2014.

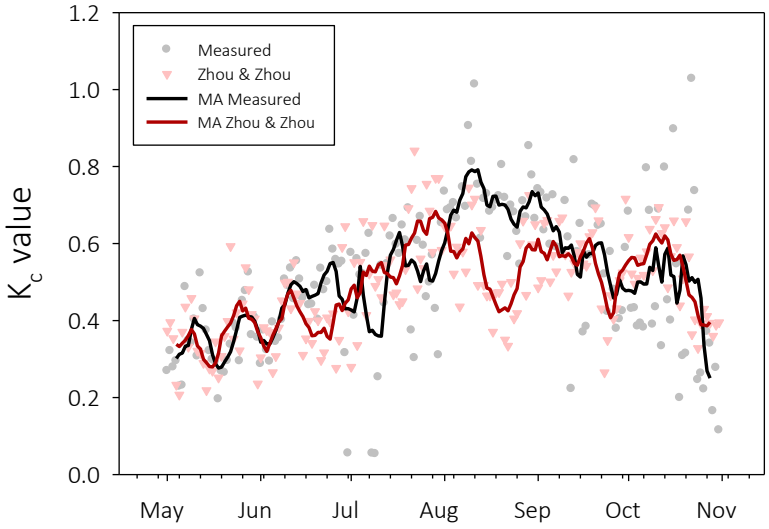

Fig. 4.6 Calculated daily K_c values from measured ET (ET_m/ET_o) (grey dots) and calculated with the regression model of Zhou & Zhou (2009) with their parameter set (pink triangles) for 2014. The black and red lines were using the moving average (MA) technique with an averaging time of 7 days.

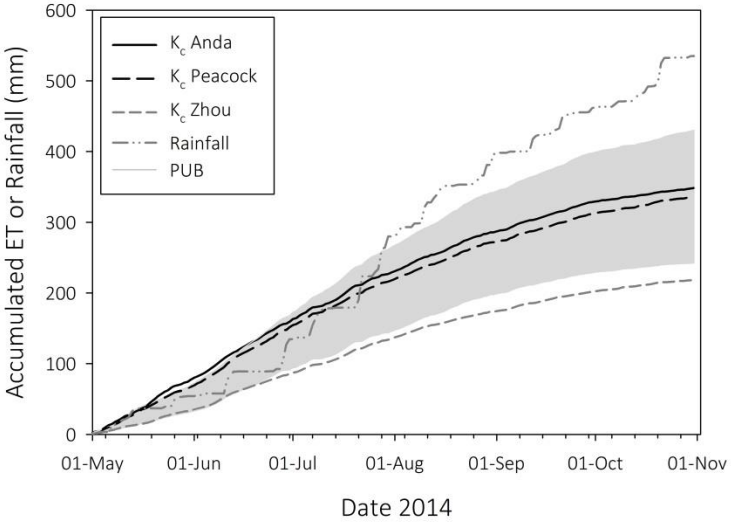

Fig 4.7 Accumulated evapotranspiration (ET) and rainfall in 2014 compared to ET calculated by the FAO method with K_c values from 3 different studies (Anda et al., Peacock and Hess., and Zhou and Zhou). The grey band shows the uncertainty of the EC data, which is caused by incomplete energy balance closure (post closure methods uncertainty band, PUB).

4.4 DISCUSSION

4.4.1 EVAPOTRANSPIRATION

In literature, the general perception is that LE dominates surface energy fluxes in wetlands (Priban and Ondok, 1985; Acreman et al., 2003), especially when dominated by *Phragmites*. This is because of the idea that *Phragmites* vegetation has the potential to transpire large amounts of water (Burba et al., 1999; Herbst and Kappen; 1999, Borin et al., 2011). Using EC, Acreman et al. (2003) found the fraction LE by Rn was 90% in a *Phragmites* wetland in England, which is far away from our findings. In contrast, we found that in the months May and October in 2013 and May, June, and October in 2014 more available energy was converted into H than into LE. In 2014 over the whole season, the average flux of H was 26% higher than that of LE. Especially at the beginning of the growing season H was very high. With increasing vegetation height and LAI, H became lower and LE increased. This means that in spring the tall, dead reed-stems heat up, while only a small amount of surface water is evaporated. The density of the reed is high, so only a small fraction of the solar radiation can reach the water surface. Due to the high density, only little turbulence can develop near the surface so that the exchange of water vapor is low (Lafleur and Rouse, 1988). Burba et al. (1999) found, on average, larger H values for *Scirpus* than for *Phragmites*. They explained it partly with a thicker layer of non-decomposed material below the *Scirpus* canopy and a larger non-green LAI. H from *Scirpus* vegetation became higher during senescence stage due to the decrease in transpiration (Burba et al., 1999). We also see that LE becomes smaller in September and October, whereas H remains more or less stable in these months, while the available energy reduced. At Acreman's site, 20% of the fetch consisted of open water (ditches) within the reed beds, which will have caused higher evaporation.

The average of our measured ET (1.3 and 2.2 mm day^{-1}, in 2013 and 2014) during the growing season, is on the lower edge of what is found in other sites with a temperate climate (between 2-4 mm day^{-1}; (Herbst and Kappen, 1999; Fermor et al., 2001; Acreman et al., 2003; Zhou and Zhou, 2009; Anda et al., 2015). A possible reason for this is that at our site the vegetation density and hence the amount of old, dead material is higher.

Summarizing the literature discussed above, there seems to be a trend that a higher plant density results in a lower LE (and ET) compared to less dense sites with more open water. So the statement of Burba et al. (1999) and Herbst and Kappen (1999) that ET from *Phragmites* wetlands may exceed open lake evaporation or even precipitation, does not hold true for our study site.

4.4.2 CROP FACTORS

FAO´s Penman-Monteith reference ET_o needs to be multiplied by the crop factor to come to the crop evapotranspiration ET_c. Anda et al. (2015) compared FAO's ET_o with lysimeter results and

created monthly crop factors. The calculated monthly crop factors from our EC data, are much lower than Anda et al. 's, 0.50 versus 0.72. This could have to do again with the high reed density at our site (see above). Peacock and Hess (2004) created crop factors by comparing ET calculated with FAO's method, with the Bowen ratio method. They found that crop factors are not consistent; K_c values were lower for dry crops with high radiation than for wet crops with low radiation. The canopy interception probably caused higher evaporation of the intercepted rainwater and the lack of stomatal resistance. However, we only found a significant difference between K_c values for rainy and dry days in the month May. The other months did not show a distinct difference, or even an opposite difference (in July). In the month May, there is not much transpiration, and evaporation is limited by the dense reed canopy. Therefore, higher evaporation rate due to canopy interception makes sense. In the other months, apparently this canopy interception is not a significant part anymore of the overall increased ET.

Criticizing that many scientists work with monthly K_c values to cover changes in the vegetation, Zhou and Zhou (2009) stress the day to day differences in K_c. They proposed to calculate daily K_c values by regression. Their model results in daily fluctuating K_c values, similar to fluctuations in K_c values based on ET_{EC} and also similar in magnitude (except for the month August). In the comparison of ET_C estimates with different K_c values from literature, Zhou and Zhou's regression model leads also to best agreement of estimated ET_c compared to ET_{EC}. Fitting the parameters of the same model to our data did not improve the model much. The model of Zhou and Zhou appears to be robust enough to be used in climatic regions as different as China and Germany. In theory, the impact of climatic variables on ET is accounted for by FAO's reference ET_o, so a subsequent regression on them is somewhat unexpected. Nevertheless, the stomatal resistance, which is part of the surface resistance, depends on radiation, temperature and RH as well (Baldocchi et al., 1987). Considering the fact that the FAO approach is based on a fixed surface resistance 70 s m^{-1}, we conjecture that Zhou and Zhou's regression model, at least partly, accounts for the variation in stomatal resistance.

4.4.3 ENERGY BALANCE AND POST CLOSURE METHODS

The EBC was on average 69%, which is around 10% lower compared to the average of the 22 FLUXNET sites (Wilson et al., 2002). The imbalance was found on every FLUXNET site, but EBC changed much per site and year (between 34-120%). At our site we had a EBC of 64% in 2013 and 74% in 2014. The common method to correct for the missing energy is to divide the missing energy over LE and H according to the Bowen ratio (Blanken et al., 1997, Twine et al., 2000). The correction method seems straightforward, but its correctness is not clear at all. There is evidence that the imbalance may often be caused by missed mesoscale eddies, which mainly affects the

sensible heat flux (Mauder and Foken, 2006; Charuchittipan et al., 2014). In this case the Bowen ratio method would lead to an overestimation of LE. PUB is a method that gives the range in which the true LE flux should be without involving further assumptions. It expresses the uncertainty in the measured data and avoids any possible wrong corrections.

4.5 CONCLUSIONS

Evapotranspiration (ET) from this *Phragmites* fen was much lower than expected from literature. Especially in May and October, when plant activity was low, the dominant flux was sensible (H) and not latent (LE) heat. This can be explained by the high density of dead reed in these months, which heat up causing a high H. Evaporation is low, due to the shading of the water layer below the canopy and low wind velocities near the surface. When *Phragmites* developed, LE increased and became a large contributor to LE.

From the crop factors (K_c) used from literature, Zhou and Zhou (2009)'s regression model yielded the best results compared to the values of Anda et al. (2015) and Peacock and Hess (2004). The regression model of Zhou and Zhou, based on measured air temperature, air humidity, and net radiation, resulted in K_c values with similar day-to-day fluctuations as crop factors based on measured ET. The dependency of K_c on these environmental variables has likely to do with a variation of the stomatal resistance, which depends on the same variables. Therefore, the model of Zhou and Zhou is a promising and robust approach to estimate daily K_c values, and its application can be recommended.

ACKNOWLEDGEMENT

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Chapter 5

General discussion and conclusions

5.1 INFLUENCE OF *PHRAGMITES* ON CH_4 FLUXES

From chapter 2 and 3 we saw that the presence of living reed has a high influence on both diurnal fluctuation and magnitude of CH_4 emission. This diurnal pattern in the CH_4 fluxes has been described before (Kim et al., 1998; van der Nat et al., 1998; Armstrong and Armstrong, 1991). Despite this, we found that the correlation between CH_4 fluxes and RH disappears when radiation increases (chapter 2, Fig. 2.7). Another reason for a diurnal cycle would be the fluctuation in the release of plant photosynthates. These photosynthates are an important carbon source for methanogens (Brix et al., 1996; Philippot et al., 2009). However, in our data we see that on average the maximum CH_4 flux appears almost at the same time as the maximum CO_2 uptake. From literature a time-shift is expected between the release of photosynthates and the production of CH_4 (Brix et al., 1996). Therefore, we conclude that the CH_4 fluxes are largely influenced by the gas transport mechanism of *Phragmites*. Apart from HIC also another mechanism has to be involved in the CH_4 release, which remains unknown from our study.

The effect of the internal pressurized gas flow on the total flux is not undisputed in literature. It could result in more CH_4 oxidation and suppression of CH_4 production in de rhizosphere, leading to a lower flux, or the CH_4 transport through the plants that bypasses the oxic layer results in less CH_4 oxidation and therefore leading to a higher flux (Grünfeld and Brix, 1999; van der Nat et al., 1998). We quantified the influence of the pressurized flow within *Phragmites* on the total CH_4 flux in a field experiment (see chapter 3) and found between 23% and 45% lower total CH_4 flux when pressurized flow was excluded (by cutting or cutting and sealing the reed). The gas transport pathways from the soil to the atmosphere changed as well. The relative contribution of ebullition to the total flux increased from 2% in intact *Phragmites* to 24-37% in cut vegetation. The suppression of ebullition by vegetation was also observed by van der Nat et al. (1998), Grünfeld and Brix (1999) and Hendriks et al. (2010). This increase in ebullition in cut vegetation, obviously, does not compensate the excluded pathway via the pressurized air flow at our site. It also means that the effect of CH_4 bypassing of the oxic water layer due to plant transport is much larger than the effect of O_2 transport by the plants on CH_4 oxidation and production in the rhizosphere. Overall, this shows that plants with pressurized gas transport mechanism are an important contributor to CH_4 emission from wetlands.

5.2 CARBON BALANCE

In the measured year (March 2013 to February 2014), this *Phragmites* fen was a net carbon and greenhouse gas sink, with an uptake of 894 g CO_2 m^{-2} yr^{-1} (26% of the assimilated carbon) and a CH_4 emission of 30 g m^{-2} yr^{-1}, resulting in a net uptake of 212 g C m^{-2} yr^{-1} and 52 g CO_2-eq m^{-2} yr^{-1}.

Our CH_4 flux is in the same range as at sites with similar *Phragmites* densities (Kankaala et al., 2004; Koch et al., 2014), but is on the higher side of other Northern peatlands (Lai, 2009). The net carbon uptake is only half as high as estimated for a *Phragmites*-dominated wetland in Denmark (550 g C m^{-2} yr^{-1}, 47% of GEP; Brix et al., 2001), but 4 times higher than a *Phragmites* wetland in China (Zhou et al., 2009). This probably largely depends on vegetation height and density and temperature (for the respiration rate). In the long term, the uptake of carbon by northern peatlands is on average between 20–50 g C m^{-2} yr^{-1} (Strack, 2008). Compared to other peatlands, our 212 g C yr^{-1} is therefore very high. A longer measurement period than one year is needed, however, to draw conclusions about the long-term C uptake for this system.

5.3 WATER AND ENERGY FLUXES

Phragmites is expected to have a high evapotranspiration (ET) rate due to the large leaf area, open water habitat and high aerodynamic roughness (Acreman et al., 2003). There is the evidence that ET from reed areas could exceed open lake evaporation (Burba et al., 1999; Herbst and Kappen, 1999, Borin et al., 2011) and even the yearly precipitation (Herbst and Kappen, 1999), which could eventually cause a wetland to dry out. From the measured ET, our site has a low ET compared to other *Phragmites* wetlands in temperate regions (Herbst and Kappen, 1999; Fermor et al., 2001; Acreman et al., 2003; Zhou and Zhou, 2009; Anda et al., 2015). ET was 50% lower than precipitation (see chapter 4). Therefore, the risk of the wetland to dry out is not realistic for our site. ET was especially low when there was little plant activity (May and October), the dominant heat flux was sensible not latent. This can be explained by the high density of dead reed in these months. This reed heats up, causing a high sensible heat flux. Evaporation was low due to the shading of the water layer below the canopy and low wind velocities near the surface. When *Phragmites* developed, transpiration increased and became a large contributor to LE.

FAO's Penman-Monteith equation appeared to be a good estimator of measured ET with monthly crop factors from the regression model of Zhou and Zhou (2009) (see chapter 4). Their model, with air temperature, relative humidity and net radiation as input variables, was able to capture day to day differences in the crop factor. The dependency of the crop factor on these environmental variables likely has to do with a variation of the stomatal resistance, which depends on the same variables (Baldocchi et al., 1987). Therefore, the model of Zhou and Zhou is an interesting approach for calculating daily crop factors and is robust enough to be used in different regions (China and Germany).

5.4 GENERAL CONCLUSIONS

The pressurized gas flow inside *Phragmites* showed to have a high impact on the CH_4 emission, as well on the timing (diurnal cycle) as on the total amount of CH_4 emission (a reduction up to 45% was observed after cutting the reed). Also ebullition is largely suppressed because of the CH_4 transport via the plants. The effect of CH_4 bypassing the oxic water layer due to plant transport was larger than the effect of CH_4 oxidation in the rhizosphere due to O_2 that is transported by the plants.

In 2013, this peatland was both a carbon sink and a greenhouse gas sink. The emitted CH_4 was more than compensated by the carbon accumulation. One year of measurements is not enough to draw hard conclusions about the climate change impact of this peatland. Therefore carbon budget for the other measured years (2014, 2016) should be evaluated as well.

Even though *Phragmites* wetlands are expected to have a large evapotranspiration rate, the actual measured evapotranspiration was low compared to literature and was around half the amount of precipitation. Especially in the beginning and the end of the growing season, the largest energy flux was sensible heat flux and not latent heat flux. Most likely the high density of *Phragmites* plays an important role in this. From the relative low ET rate we conclude that the dry-out of this peatland is not likely.

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EDUCATION

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Sep 2004 – Oct 2007	Bachelor Biology with a track in Environmental Sciences (Radboud University, Nijmegen)
Sept 1997 – Jun 2004	VWO, highest secondary school level in the Netherlands

WORK EXPERIENCES

Nov 2017 – now	Postdoc position at the Radboud University (Nijmegen).
Sep 2012 – Nov 2017	PhD research at the University of Hohenheim with the aim to measure and understand carbon fluxes (CO_2 and CH_4), and energy and water fluxes from a reed-vegetated fen in southwest Germany (see publications).
Sep 2010 – May 2011	Master thesis research at the Universidad de Cuenca (Ecuador) and Wageningen University, in which different downscaling methods, to come from global climate predictions to a local scale, were compared to predict future changes in river discharge with a rainfall-runoff model (MIKE HYDRO) in the Ecuadorian Andes.
Jan 2010 – Jun 2010	Internship at WWF-Netherlands, with the aim to analyse the worldwide freshwater projects to see how intact or restored ecosystems can buffer the impact of climate change.
Jan 2009 – May 2009	Part-time job at the Wadden Academy to write a section for the position paper *Climate and Water* as part of the integrated research agenda of the Wadden Academy (see publications).

PUBLICATIONS

Van den Berg, M., Van den Elzen, E., Ingwersen, J., Kosten, S., Lamers, L. M. P., Streck, T. Contribution of plant-induced pressurized flow to CH_4 emission from a *Phragmites* fen (submitted to Soil Biology & Biochemistry).

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AWARDS

Outstanding Student Poster Award 2014 Biogeosciences, European Geosciences Union General Assembly 2014